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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM 1318

FRICITION AND WEAR

By J. Pomey

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TABLE OF CONTENTS

	Page
CHAPTER 1.- GENERAL REMARKS ON FRICTION AND WEAR	1
1. Friction	1
2. Wear	4
3. Scale of Observed Phenomena	4
4. Attainment of Surface Conditions	7
5. Heat Phenomena	12
CHAPTER 2.- HYDRODYNAMIC LUBRICATION	17
6. The Osborne Reynolds Oil Wedge	17
7. Application of the Oil Wedge Theory	24
8. Establishment of the Steady State	27
9. Run-In	28
10. Shock Phenomena by F. Charron	29
11. Smectic State and Lubrication by Stratified Layers	31
CHAPTER 3.- GREASY (BOUNDARY) FRICTION	35
12. Use of Herschel's Apparatus	35
13. Changes Due to Corrosion	38
14. Saturation Effect	40
15. Noble Metals and Reactive Metals	41
16. Metallic Couples	42
17. Esters	44
18. Different Fatty Acids	45
19. Compounding of Lubricating Oils	45
20. Hypothesis of the Mode of Action of Fatty Acids	46
21. Rolling Contact Bearings	47
CHAPTER 4.- SEIZURE	51
22. Mechanism of Welding by Comparison	51
23. Mechanism of Seizure	52
24. Measurement of the Coefficient of Friction under High Pressure	53
25. Extreme Pressure Lubricants	53
26. Synoptic Table	56
27. Abrasion Due to Dust	57
28. Corrosion Friction	57

	Page
CHAPTER 5.- DRY FRICTION	59
29. Steels	59
30. Dry Friction of Other Alloys	64
CONCLUSIONS	67

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CHAPTER 1

GENERAL REMARKS ON FRICTION AND WEAR

1. Friction

In rational mechanics, several kinds of friction are defined.

(1) Viscous friction of liquids:

Visualize the simplest case where the motion of a viscous fluid is reduced to the sliding of parallel planes. Consider (fig. 1) the surface element dS of a plane moving at speed V , with $V + dV$ representing the speed of the plane parallel to V at infinitely small distance dn . The force of the friction F exerted on the element dS is

$$F = \eta \frac{dV}{dn} dS$$

where η is, by definition, the coefficient of viscosity. F is a shearing force. The viscosity is therefore the property by which the relative motion of the molecules of a fluid mass is restrained as a result of friction or sticking exerted between them. The coefficient of viscosity increases, therefore, with the pressure.

(2) Internal friction of solids:

When a solid is subjected to a system of forces, each element of volume is affected by a system of normal stresses of proportional deformations, hence purely elastic and reversible, and by a system of tangential stresses producing slipping which are not reversible since they are accompanied by friction. This friction increases as the surface elements to which they are referred are subjected to higher pressure and the deformation is more rapid.

*"Le Frottement et L'Usure." Office National d'Etudes et de Recherches Aeronautiques Rapport Technique No. 36, 1948. Travaux du Groupement Francais pour le Développement des Recherches Aéronautiques (G.R.A.).

If the applied forces vary according to a periodic law, the steady state is established at the same time as the deformations. The work of internal friction in each elementary volume represents the energy expended and reduced in the form of heat. In the case of the simple stress of a prismatic test piece, it is given by the area of the stress-strain cycle (fig. 2). It also is responsible for the damping of the free oscillations. This internal damping is then defined by the logarithmic decrement of these damped oscillations.

(3) Sliding friction between solid bodies:

Consider two bodies pressing upon each other; N (fig. 3) denotes the force of pressure keeping these two bodies in contact. Then assume that both are moved in such a way that they remain subjected to contact. The point of contact is displaced on the surface of both of these bodies and at this point of contact a restraining force or friction $F = N \tan \phi$ along the tangential plane in a direction opposite to that of the relative motion is produced; $f = \tan \phi$ is the coefficient of friction.

(4) Rolling friction:

Consider two bodies in contact, with N representing the force of pressure assuring the contact. Assume that without sliding, one of the bodies is made to roll on the other (fig. 4). The center of instantaneous rotation is located precisely at the point of contact; a restraining couple Nh arises, where h is the parameter of rolling. The normal reaction N is considered as being applied, not at the point of contact, but ahead of it in the direction of rolling and at a distance h from the point of contact. Let us examine the phenomenon a little more closely. Consider, for example, the particularly simple case of a sphere rolling on a plane. Instead of a point of contact as a result of elastic deformations of the sphere and of the plane, the contact takes place along a small circle and the diametrical distribution of the stresses is elliptic, the stress being maximum at the center of the contact circle and zero at its circumference.

The contact occurs along an ellipsoid, not along a plane. Under the effect of the pressure at each point of the surface of contact, the material has undergone a displacement and if the elastic moduli of the two bodies are not the same, the elastic displacements are different and there is sliding of one surface over the other. On the other hand, with rolling, a point of the sphere coming into contact has its contact pressure increase from zero to a maximum, then decrease to zero. The result is a certain internal friction and the energy supplied during the cycle is not zero. The friction of rolling can be regarded as the sum of the sliding friction of the different points coming successively in contact and of the internal friction due to the cyclic deformation.

(5) Pivoting friction:

It is merely pointed out that this is a special case of sliding friction.

(6) General case of friction of solid bodies:

As a result of irregularities in the contact surfaces, each body is subjected by the other to the action of an infinity of stresses distributed over the contact area.

In consequence of the roughness of the surface these stresses can present very different directions from one another. In these conditions, the system of forces acting on each body is reducible to a force applied to an arbitrary point at the contact area and to a couple. The resultant force must be resolved into a normal component or pressure force and a tangential component or sliding friction.

The resultant couple can be resolved into two others, one whose axis is normal to the contact area, or pivoting couple, the other whose axis is tangential to this surface, or rolling couple.

(7) Physical aspect of friction:

In a more realistic examination of the problem of sliding, two elastic bodies, each limited by a surface with a fluid interposed between them, have to be considered. The definition and nature of the contact will be discussed later. The fluid between the two solid bodies plays a nonnegligible part. It can adhere strongly to the surfaces by adsorption and remain as a thin film in spite of the pressure force, or, in other cases, remain interposed by hydrodynamic entrainment as a result of its viscosity and the high relative speed of the surfaces. In the latter case during sliding, the work of the force of friction releases heat to such an extent that heat phenomena should be considered. Besides, the surrounding medium may react on the material of the solid surfaces and this is generally so much better with heating, by causing chemical reactions which must also be taken into account as well as the products of these chemical reactions which might again cover the surfaces. From this, it is readily apparent that friction assumes a complicated aspect from the physical point of view and varies with the relative influence of the different factors previously discussed.

It is also seen that the chemical reactions entail losses of material, which is one of the forms of wear by friction.

(8) Examples of coefficients of friction:

Table I below gives some coefficients of friction covering all ranges; it shows the considerable influence of the interposed liquids on friction; case of water on rubber, or of the fatty acid between two metals.

TABLE I.- COEFFICIENTS OF FRICTIONS

rubber/road	{ dry wet	1 to 0.6 0.6 to 0.2
metal/metal	{ dry fatty or smectic lubrication viscous or boundary lubrication	0.5 to 0.15 0.10 to 0.035 0.05 to 0.001

2. Wear

The loss of material between two rubbing surfaces is called wear. It can assume as many aspects as friction itself so that the two problems are inseparable. The wear may be mechanical, physical, or chemical.

(1) Mechanical wear:

Wear is mechanical when the material is broken up in the manner of filings as a result of geometric irregularities of the rubbing surfaces or by rough abrasive dust which acts like small tools, or it may be due to the break up of soft friable or malleable constituents such as graphite or lead.

(2) Physical wear:

Wear is physical in the case of seizing which permits the two pieces rubbing against one another to weld, which is followed by the shearing necessary for the continuation of the motion.

(3) Chemical wear or corrosion:

Wear is chemical in the case of oxidation of metal in the air, or when metal sulphur compounds form in sulphurized oil, or when the metal in a fatty oil is attacked by the fatty acid with formation of soap.

3. Scale of Observed Phenomena

The geometric irregularities in solid surfaces made to rub against one another, the internal structure of metallic bodies near the surface, and the artificial phenomena stemming from the surrounding medium are other groups of factors to be considered in friction. For this reason it

seems advisable to collect them in a synoptic table and, since they can be referred to entirely different orders of magnitude, to classify them on a length scale. This is accomplished in table II.

TABLE II.- SYNOPTIC TABLE OF THE PHENOMENA STUDIED,
CLASSED ACCORDING TO SCALE OF OBSERVATION

Scale of observation	Method of investigation	Geometric irregularities of the surface	Body structure annealed, machined, polished	Phenomena in the surrounding liquid	Remarks
2 to 3 Å	Electron diffraction		Layer of electronic passage gaseous adsorption	Atmosphere created by valence electrons. Field of attraction	Responsible for electric contact of adherence, welding, filiation, and epitaxis [arrangement].
23 to 46 Å		Optical surfaces	Amorphous Bellity layer	1 fatty layer, C. 18 2 fatty layers, C. 18	Greasy lubrication under high pressure, low speed
100 Å	Resolving power, electron microscope				
250 Å	Interference of light				
500 Å	Feeler with electric amplifications	Fine superfinish			Overlapping [irregularity] variable with stresses developed by machining
1500 Å		Medium superfinish, fine electrolytic polishing			
2000 Å	Resolving power, optical-microscopic				Overlapping [irregularity] variable with pressure, speed, and viscosity
2500 Å		Rough superfinish and honing			
3000 Å	(Ultra-violet)	Fine grinding, rough electrolytic polishing			
6000 Å	(Orange)	Medium grinding			
9000 Å = 0.9μ	(Infrared)	Rough grinding			
50,000 Å = 5μ	Johanson gage blocks	Limits of very fine machining			
100,000 Å = $\frac{1}{100}$ mm	Classical metrology, micrometer gages and calibers	Machining with precision tool			Limits of macrogeometry of surfaces

At the bottom of the scale are found the interatomic distances of the metallic crystals which are of the order of 2 to 3 Å. Hence, there are two manifestations to this scale, one of the inside, the other of the outside of the body.

The gases adsorbed by the metallic surfaces are arranged in the gaps between the atoms of the first reticular layer.

In metals, the valence electrons move in the entire volume of the crystalline system which, by this fact, is a conductor of electricity, and they proceed only to be removed very little, to a maximum distance, the order of magnitude of which does not exceed the length of the link, by creating around the body an electronic atmosphere responsible for electric contact. It is at this same distance at which are exerted the forces of cohesion between bodies, the adherence by welding, filiation, and epitaxis. The last property is particularly important. It can be defined as the faculty which a crystalline species has in the formative stage of developing in contact with a preexisting crystalline surface which orientates the crystallization.

For perfect epitaxis (arrangement) it is necessary that certain nodes of the crystalline system, in the formative stage, be made to coincide with certain nodes of the preexisting directing system (Friedel). The forces of attraction may be those of Van Der Waals and in that case the orientation and the union is precarious as, without great rigidity, or by contrast, these forces can be electrostatic and in that case the new crystalline species is very energetically welded to the old.

Consider now what happens in a metallic body of greater depth.

The stresses developed in the mechanical preparation of the metallic surfaces produce internal tensions which may be high enough to destroy the preexisting crystalline system; then there is work hardening. The latter is so much more pronounced, when we consider the layers closer to the surface where the structure loses all crystalline character, that is, the amorphous Beilby layer.

Among the superficial phenomena which develop in the ambient medium, there is one of particular importance, namely, the tendency to form molecular films of fatty bodies, which will be subsequently studied with special care by reason of its importance in greasy friction. The natural fatty molecules, vegetable or mineral (Devaux, Woog, Well and Southcombe, Trillat), are characterized by a chain of carbon atoms having most frequently 18 carbon atoms. The order of magnitude of the monomolecular layers is always the same. Now if we consider the stacking of molecular layers, orientated as in smectic liquid crystals easily orientated by epitaxis (Mauguin, Grandjean), the thicknesses of the liquid layers can grow by equal stages from the monomolecular layer to the thick liquid layers in hydrodynamic flow of viscous liquids.

As to the physical methods of analyzing the crystalline structure, the most superficial method is by electron diffraction, because the electrons penetrate only the first reticular layers whereas X-ray diffraction enables the crystalline system to be studied in its mass.

As far as the examination of the surfaces is concerned, the microscope is limited by its defining power

$$\frac{0.61\lambda}{n \sin u}$$

where u is the numerical semiaperture, n the index of refraction of the medium into which the sample is dipped, and λ the wave length of radiation. The microscope with visible light and immersion is limited to 2000 Å. The use of shorter ultraviolet radiations increases the complications without great benefit. On the other hand, considerable progress has been made with the electronic microscope whose wave length associated with the electron of mass m (De Broglie) is very short and given by the formula

$$\lambda = \frac{h}{mv}$$

where h is Planck's constant, v the speed of the electron. The drawback is that by reason of the weak penetration of the electrons, the study of metallic surfaces is made indirectly by double transfer. First, an impression is taken on polystyrene and a film of silica deposited over it by evaporation in a vacuum; then, the polystyrene is dissolved leaving the transparent replica of the opaque surface of the specimen. The resolving power reaches 100 Å.

4. Attainment of Surface Conditions

Since rough surfaces cannot slide freely, the surface conditions must be improved so as to approach as nearly as possible the ideal geometric surfaces which enable one surface to slide easily on the other.

(1) Charpy-Caquot adaptation:

The defects of machining and mounting result in irregular distribution of the pressure which may reach excessive values at certain points unless Caquot's principle of adaptation is employed. The bearing metals must deform to assure a better pressure distribution. They must, besides being of low elastic modulus, be soft enough to produce considerable permanent deformations when they are initially put in service, hence the

use of alloys with bases of lead, tin, cadmium, copper, or silver. The softness of copper is improved by giving it a porous structure (self-lubricating rings impregnated with oil) or by distributing extremely fine and regular inclusions of lead obtained by quenching from the liquid state of a homogeneous copper-lead alloy; rapid cooling is necessary to avoid liquation of the lead. By reason of their softness, the white metals have a low endurance limit and tend to flatten out. A compromise must therefore be attempted between these contradictory properties in each particular case. Thus the addition of 1 percent cadmium, for example, multiplies the creep strength of lead base babbitt metal (Sb 8 to 10 - Cu 3.5 to 6) by 1.5 by raising the endurance limit from 3.2 to 3.8 kilograms per millimeter². These drawbacks can also be remedied without sacrificing softness, as will be shown later.

The more carefully the machine is designed for presenting rigid forms, the more the surfaces are polished, the more accurate the adjustment is made, the more the amplitude of deformations demanded from the bearings can be reduced, and it becomes possible to use babbitt metal in very thin layers whose creep is considerably impeded. In fact, the thin bushings referred to make it possible to support loads in normal service 1.5 times greater than the old bushing of the same babbitt metal, with the result that their usage has become universal in modern machines.

To ensure minimum wear the bearing surface should, according to Charpy's theory, consist of hard constituents to equalize the pressure, the hard constituents being embedded in a soft matrix in which they are set. Typical compositions are the cubic compounds Sb Sn of lead-base babbitt metal and of the cubic composition N.Cd₇ of cadmium base bearing alloys.

In certain gears designed for severe service such as the rear axle of an automobile, a certain adaptation by a slight hypercooling (tempering) of the tempered casehardened surface layer is recommended. The remainder of the austenite permits a very slight permanent deformation in the wearing in period which improves the pressure distribution along with the internal stresses near the surface.

In all cases where heavy loads are involved, that is, particularly in the case of annealed hard steel or hardened carburized steel, it is not enough to remove the macrogeometric irregularities of the surface; the slightest ones must be removed as well because the least irregularity in the surface is accompanied by a considerable local rise in pressure due to welding which causes an exaggerated friction with breaking up of material. Furthermore, these surfaces must be particularly well polished. It is obtained by what is called a superfinish, of which there are two categories.

(2) Mechanical superfinish:

The superfinish invented by David A. Wallace is a honing process with very soft stones of coarse abrasive grains at extremely low pressure; the final pressure does not exceed 0.35 kilograms per centimeter² on an average. This operation is effected with abundant washing to remove all abrasive grains or any other small metal filings previously loosened. The polishing is done with random motion such that the stones never traverse the same path. At the start of the operation the honing stone bears only on the rough spots of the surface assuring a small area of contact and as a result of the high local pressure produces a rapid abrasion on the area to be polished. As wear progresses, the contact area increases, the pressure decreases, and finally the wetting liquid is entrained hydrodynamically between the stone and the area to be polished after which the polishing stops automatically. The entire operation takes from 10 seconds to 3 minutes.

The operation is represented in figure 5. Only the bottom of the deepest scratches are left; their removal would increase the area of contact rather little and even then only at the expense of a laborious operation.

After removal of these cavities or scratches the surface is not exactly flat; it still presents deformations which recall the initial undulations of the profile. As a general rule the macrogeometric irregularities of the profile are not removed but reduced by 50 percent. From the practical point of view a suitable area of contact is obtained when the geometric surface can be obtained by elastic deformation of the actual surface. In any case, the process of mechanical superfinish affords a substantially greater area of contact with a number of attendant advantages, namely:

- (a) Reduction of clearance by a suitable preparation of the piece having as consequence a reduction of the levelling effects and oil leakages
- (b) Increase of the load causing incipient seizing
- (c) Less wear by elimination of abrasive grains and by removal of the roughnesses of the piece which may scratch the bearing metal; it is in particular demand for case hardened crankshafts mounted in copper-lead bearings
- (d) Decrease of the viscous friction arising from decrease of the thickness of the viscous liquid (see fig. 15); the coefficient of friction can be lowered to 0.002

(3) Electrolytic superfinish by Jacquet:

The electrolytic polishing process is still too obscure in its principle for one to give a complete or exact theory; however, a certain number of phenomena make it possible to give a relatively simple explanation of the phenomenon which, because of its utter simplicity, is described hereinafter.

Let us suppose an anodic surface to be polished is dipped in an electrolyte parallel to a cathodic surface. The liquid is such that the metallic salt arising from the anodic attack of the metal enters in combination with the products of electrolyte liquid to produce complex salts of very great volume, viscous and dissociated, which involves the formation of layers of great resistivity that slowly diffuse, normally at the anode.

At sufficiently strong current densities this viscous layer presents characteristics such that the ohmic drop between anode and cathode, for the greater part of the distance of the lines of current in the liquid, is localized in this diffusion layer.

The result, according to figure 6, is that the lines of the current which terminate at the inside of the constricted cavities will have to traverse a resistant viscous layer of considerable thickness, and it is the reverse in the prominent part. At the end of a certain time of electrolysis, the irregularities in the surfaces are removed and a very beautiful specular polish is obtainable.

The study of the fine structure of the surface indicates that the small cavities disappear completely and quickly, although the deep cavities are scarcely diminished (figs. 5 and 6). The outer macrogeometric surface retains the same macrogeometric deformations as the initial surface unless it is remedied by special mountings including plates of opposite polarity or screens, but the outstanding characteristic is the round aspect of the cavities.

The electrolytic polishing process increases the curvature radius considerably and promises an improvement in corrosion resistance. It is shown in the case of stainless steel of 18 Cr 8 Ni but not in magnesium alloys.

The increased curvature radius of the convex parts make it possible, if we keep in mind the elastic deformations in service, to increase the load-carrying capacity of the surface and to reduce the maximum pressure.

The increase in the radius of curvature of the convex parts should lead to a better endurance limit. It was discovered that polishing lengthwise mechanically produced no improvement on the usual specimens;

the improvement existed only in relation to specimens machined roughly or polished perpendicular to the direction of the stresses.

The attack in depth of the surface layer should, it is believed, bring about the removal of the amorphous Beilby layer and of the greater part of the cold-hardened layer, and with it the possibility of obtaining, by epitaxis a monomolecular layer of fatty acid on these surfaces which will be slightly more dense, more rigid, and better qualified for greasy lubrication. Experience does not seem to confirm these hopes.

Our own experiments have shown no reduction in the coefficient of greasy friction by stearic acid on an electrolytically polished surface. In other respects the study, by electron diffraction under flat incidence undertaken by J. J. Trillat, gave no inkling of the character of the crystalline structure.

The electrolytic polishing process has, by way of contrast, several drawbacks:

- (a) It does not diminish the depth of the largest surface irregularities which are simply rounded
- (b) It involves the removal of material causing a consequential modification of the dimensions
- (c) It is not applicable to steel under internal stresses, hardened steel or extra soft steel which has been case hardened, as they would develop surface cracks, that is all the more damage because the pieces made of these steels are precisely those for which the best surface finish is desired.

(4) First limit of application of superfinish:

The superfinish, whatever its mode of obtention, is a supplementary operation, rather difficult and expensive, which therefore is of interest only to the extent to which two surfaces designed to rub against one another are identically superfinished and to the extent to which the clearance between the surfaces is reduced. It is useless to superfinish the piston pins if the hard bronze bearings in which they pivot are rough machined, hence of limited area of contact, or with excessive clearance which flatten the piston pin under the effect of the repeated shocks due to the inertia of the piston.

On the other hand, the superfinish does not accord with burnishing or shot blasting which are used for producing a surface layer in hydrostatic compression by deforming the surface by a multitude of small indentations, thus lowering the sensitivity to notch effect and raising the endurance to alternating stresses substantially. Not wishing to

dwell any further upon this important question which is outside the framework of the phenomena of friction and wear, it is simply stated that its importance is such for the behavior of the pieces in service that in many cases it is preferred in surface finishing.

5. Heat Phenomena

(1) Surface temperature:

The experiments by Bowden, Ridler, and Hughes in 1936 and 1937 at the University of Cambridge were made with the apparatus of figure 7.

A rubbing surface is formed by the metal A in the form of a flat disk of large diameter rigidly mounted on a cylinder with vertical shaft which is driven at an appropriate speed. A round metallic friction piece S of small diameter and vertical shaft is carried by a straight section on rubbing path A of the cylinder. The friction piece is attached to a rigid arm R and a gimbal J. A hook on arm R serves for loading the friction piece by the weight W. A light rod connects the friction piece with a pendulum D in such a way that the friction piece cannot be carried along by the rotation of the cylinder. The rubbing force can be measured by the deflection of the pendulum D which consists of a heavy mass L, a damper V, and a mirror C near the axis of oscillation with agate bearing and a knife edge of steel. An electric lamp E lights up the mirror and the spot of light moves on a vertical scale F; an Einthoven galvanometer G is hooked up between the rubbing piece S and the disk ring A to which it is connected by a contact rotating in a bath of mercury at the axis of the cylinder.

With rubbing pieces of fusible metal their fusion temperature can be reached but not exceeded because at the point of contact, the release of the heat causes the metal to melt which runs out in diminishing the roughness and in increasing the area of contact. The fusion is easily identified by a micrographic examination of the rubbing surface.

With friction pieces of less fusible metal, the temperature must be measured by pyrometer. It is impossible to ascertain the surface temperature even with a thermocouple mounted inside the friction piece no matter how close it is to the surface because the temperature measurement will be lower by reason of the unknown temperature gradient; hence, it is imperative that the hot junction be formed by the rubbing surface itself. The galvanometer hooked up between the ring and the friction piece gives then the temperature of the rubbing surface at the points of contact. The only condition is that the thermoelectric force of contact of the couples of the two metals in question have been previously determined. It was found that temperatures of 800° to 1000° C are easily attainable.

The lubrication with mineral oils is very inadequate since the oil is expelled, the film is continuously torn and continuously formed again; this film, however, supports a nonnegligible part of the load, the pressure in the solid contacts is reduced and with it the temperature also, which proves that, without being perfect, lubrication can have a favorable effect. Moreover, the oil is easily altered as a result of the high temperature.

Lastly, the high temperature attained shows that the micrographic structure of the surface layers is profoundly altered by friction; such is particularly the case with the Beilby layer.

(2) Heat distribution:

How is the heat distributed between the two pieces rubbing against one another? Vernotte explained it theoretically in 1938 and Charron answered it experimentally in 1939 with the setup shown in figure 8.

An electric motor drives a wheel with upright shaft comprising three insulating vertical tips on which rests a metal disk whose axis coincides with that of the wheel. This disk is set in rotation by the three vertical tips which mesh into recesses provided for it. The upper horizontal plane surface of this disk is brought in rubbing contact with the lower horizontal plane surface of another disk of the same dimensions but of different metal and kept stationary and under pressure by means of a heat-insulating support.

At the end of a certain rubbing period, the upper disk is put in one calorimeter and the lower disk into another, and the amount of heat absorbed by the corresponding disk recorded.

It is found that the quantity of heat taken up by a disk is proportional to \sqrt{Kcp} , where K is the thermal conductivity, c the specific heat per unit of mass, ρ the density, and the product cp the heat capacity per unit volume.

(3) Calculation of contact temperature:

Consider two bodies brought into contact by a force of elastic pressure. This area of contact is an ellipse and the pressure can be represented according to H. Hertz by the ordinates of a semiellipsoid constructed on this area of contact. The maximum pressure at the center is 1.5 times the average value. The area of contact of one body slides over that of the other at speeds V_1 and V_2 , respectively, which can vary in time. Blok has computed the maximum temperature by considering the specific case of gears for which the surfaces of the teeth are in contact under very high pressure on a very elongated ellipse which, in the case of spur gears, is reduced to a straight rectangular band of width $2l$ parallel to the gear shafts.

The rolling friction is negligible compared to the sliding friction. At each point and at every instance, the heat released by friction is proportional to the pressure and the sliding speed such that the law of distribution of the released heat is substantially the same as that of the pressure.

If P is the applied load per unit of length of the contact band, the heat released, expressed in unit of work per unit of time and per unit of length of the band, is

$$Q = FP(V_2 - V_1)$$

and is distributed between the two pieces. The area swept by the contact is different on each one of them since the speed of displacement of the contact is not the same. The result is that at each instant the heat is not only distributed proportional to \sqrt{Kcp} but also proportional to the square root of the swept area exposed to the heat flow, that is, proportional to the square root of the speed of displacement of the contact on each of the bodies; hence the formula

$$\frac{q_1 \sqrt{K_1 c_1 \rho_1} \sqrt{V_1}}{q_2 \sqrt{K_2 c_2 \rho_2} \sqrt{V_2}}$$

where q_1 and q_2 are the heat dissipations per unit time by each one of the two pinions.

The maximum temperature reached in contact is proportional to the volume of heat Q released per unit of time and unit of length of the band, but it is also so much lower as the heat is better diffused by the bodies in contact; hence, it is inversely proportional to the square root of the product Kcp by the swept area, which itself is proportional to the width $2l$ of the band and to the rate of sweeping V_1 or V_2 ; hence, the formula established by Blok

$$\theta = c \frac{Q}{(\sqrt{K_1 c_1 \rho_1} \sqrt{V_1} + \sqrt{K_2 c_2 \rho_2} \sqrt{V_2}) \sqrt{2l}}$$

where c is a dimensionless numerical coefficient. In the case of spur

gears, if R_1 or R_2 are the radii of curvature of the tooth surfaces, Hertz's formula gives

$$l = \sqrt{4P \left(\frac{1 - \sigma_1^2}{E_1} + \frac{1 - \sigma_2^2}{E_2} \right) \frac{R_1 R_2}{R_1 + R_2}}$$

where σ is Poisson's ratio and E is Young's modulus. If N is the number of revolutions per unit of time

$$V_1 = \alpha_1 N$$

$$V_2 = \alpha_2 N$$

and the maximum temperature is expressed as function of N , F , and P

$$\theta = \frac{c}{2} \frac{F \sqrt[4]{P^3 N^2 (\alpha_2 - \alpha_1)}}{(\alpha_1 \sqrt{K_1 C_1 \rho_1} + \alpha_2 \sqrt{K_2 C_2 \rho_2}) \sqrt[4]{\frac{1 - \sigma_1^2}{E_1} + \frac{1 - \sigma_2^2}{E_2}} \sqrt[4]{\frac{R_1 R_2}{R_1 + R_2}}}$$

The following conclusions are drawn:

(1) It is not the product PV which must be considered but $\sqrt[4]{P^3 N^2}$ with its predominate contribution to the pressure.

(2) For hypoid gears of steel under high pressure (3 to 10 kg/mm²) and high rate of sliding (3 to 10 m/sec) the application of this formula - using $f = 0.1$ - indicates that temperatures of from 300° to 400° C can be attained. For the latter, the use of ordinary kinds of oils for lubricants is then no longer possible and in order to avoid seizing it may become necessary to resort to extreme-pressure lubricants which, as will be shown later, are corrosive liquids containing sulphur or phosphorous.

As regards the choice of materials the factors

$$\sqrt{K_1 C_1 \rho_1} \quad \text{and} \quad \sqrt{K_2 C_2 \rho_2}$$

and also Hertz's elastic factor

$$\sqrt{\frac{1 - \sigma_1^2}{E_1} + \frac{1 - \sigma_2^2}{E_2}}$$

are involved. If the two gears are made from the same materials, the temperature reached at contact is inversely proportional to

$$\sqrt{Kc\rho} \sqrt[4]{\frac{1 - \sigma^2}{E}}$$

which can be used for classifying the materials. In practice, the classification so obtained is little different from that resulting from the simple consideration of thermal conductivity which is the deciding factor.

Pure copper is a metal which, in the foregoing conditions, gives the lowest contact temperature. Next comes silver, followed, in succession, by two alloys of copper in which the copper constitutes a solid phase (remaining in the pure state and thus giving good thermal conductivity). These alloys are the copper-lead alloys, soft alloys perfectly suitable for bearings, and the very hard Cu-Ni-Si alloys in which Ni and Si, in the form of hard intermetallic combinations of Ni_2Si , are finely distributed by tempering and annealing (structural hardening).

The Ni-Si bronzes are very tough and of very good thermal conductivity and perfectly suitable for high friction pinions; they are also recommended in worm gears; with the worm made of hard steel, the wheel of Ni-Si bronze, for example. The local surface heating of steel gears under high load during the wearing-in period can be reduced by an electrolytic deposit of brass rich in Cu which has a good thermal conductivity and a low elastic modulus.

Fusible metals should be classified not according to the temperature attained but according to the ratio of fusion temperature to temperature attained; the order would then be as follows: cadmium, lead, tin. The superiority of cadmium is very obvious; the danger of fusion in service is substantially less than with tin base bearing alloys.

CHAPTER 2

HYDRODYNAMIC LUBRICATION

Hydrodynamic lubrication refers to that movement of a surface against another, without solid contact because of the build-up of hydrodynamic pressure of a lubricant film between the surfaces. The pressure which is opposed to the contact in spite of the load is not due, as in hydraulics, to the constancy of the Helmholtz function H which expresses the constancy of energy of an ideal fluid element along a trajectory in permanent flow, but to the viscous character of the natural fluids and is produced even at relatively low velocities of flow. This viscous friction involves less energy loss due to heat.

The mode of action of viscous liquids is evidenced, in theory, by Reynolds's oil wedge described in the following.

6. The Osborne Reynolds Oil Wedge

(1) Theory of oil wedge:

The presentation differs little from that given by M. F. Charron.

In the simplest schematic case the wedge (fig. 9) consists of three parts:

- (1) The infinite plane surface xoy moving along ox at speed $u = -u_0$
- (2) The fixed plane surface between the straight lines mm' and nn' parallel to oy and at distances h_0 and h_a from ox , the lengths of h_0 and h_a are very small; the distance from mm' to nn' is a , the angle of the two planes and hence the slope α are assumed small
- (3) The fluid inserted between these two surfaces which is assumed to be homogeneous, isotropic, incompressible, and viscous

The geometric reaction is

$$h - h_0 = (h_a - h_0) \frac{x}{a} = \alpha x$$

where h designates the ordinate of the points of the fixed plane of abscissa x .

It is known that the molecules of a viscous liquid in contact with a surface have the same speed as the latter. The liquid film in contact with the plane xoy has therefore the speed $-u_0$, while the liquid in contact with the plane $mm' nn'$ is at rest.

Suppose that by reason of the thin film the component of the speed along axis OZ normal to the film is negligible in every point; likewise, that the component u of the speed along ox is subjected to weak variations $\frac{\partial u}{\partial x}$ in the direction of flow ox which are negligible compared to the $\frac{\partial u}{\partial z}$ which this same component undergoes in the direction OZ normal to the film. The pressure p can then be regarded as constant in a straight section of the stream; it depends only on x .

Consider (fig. 9a) the equilibrium of an elementary parallelepiped of edges dx , dy , dz at any one point of the fluid of coordinates x , y , z . The tangential stress exerted on the plane element $dx dy$ of the fluid is, by definition for viscous friction:

$$T = \eta \frac{\partial u}{\partial z} \quad (1)$$

The two surfaces of the wedge being close to each other, the viscous forces are very great and, compared with them, the mass forces and the inertia forces can be neglected.

The resultant of the forces projected on OX is zero

$$\left[-\left(p + \frac{dp}{dx} dx \right) + p \right] dy dz + \left[\eta \left(\frac{\partial u}{\partial z} + \frac{\partial^2 u}{\partial z^2} dz \right) - \eta \frac{\partial u}{\partial z} \right] dx dy = 0$$

or simply

$$-\frac{dp}{dx} + \eta \frac{\partial^2 u}{\partial z^2} = 0 \quad (2)$$

which is the equation to which the infinite hydrodynamic equations are reduced in the simplified case in question.

To this must be added the equation of continuity which expresses the constancy of output

$$\int_0^h u \, dz = -q \quad (3)$$

q represents the output of a section of width $y = 1$.

The pressure p depends on x only, p being equal to the atmospheric pressure H at the two ends of the oil wedge, i.e., for $x = 0$ and $x = a$; the pressure passes through a maximum or a minimum, for this case $\frac{dp}{dx} = 0$, equation (2) shows that $\frac{\partial^2 u}{\partial z^2} = 0$; hence in the corresponding straight section u varies as a linear function of z .

For $z = 0$, $u = -u_0$ and for $z = h_m$, $u = 0$; when h_m is the value of h for this section the output q is

$$q = \frac{u_0 h_m}{2}$$

and the equation of continuity reads

$$\int_0^h u \, dz = -\frac{u_0 h_m}{2} \quad (4)$$

Since p is solely a function of x , equation (2) can be integrated twice with respect to z , so that

$$u = \frac{1}{2\eta} \frac{dp}{dx} (z^2 - hz) + u_0 \frac{z - h}{h} \quad (5)$$

Introducing this expression of u in equation (4) and integrating with respect to z gives

$$\frac{dp}{dx} = -6\eta u_0 \frac{h - h_m}{h^3} \quad (6)$$

for $h < h_m \frac{dp}{dx} > 0$, which shows that p passes through a maximum.

The pressure in any point of the coordinates x, z is given by the integral $\int \frac{dp}{dx} dx$; taking h as independent variable and integrating gives

$$p = -\frac{6a\eta u_0}{h_a - h_0} \left[-\frac{1}{h} + \frac{h_m}{2h^2} + C \right] \quad (7)$$

C denoting a constant such that $p = H$ for $h = h_0$ and $p = H$ for $h = h_a$; this enables h_m and C to be determined

$$h_m = 2 \frac{h_0 h_a}{h_0 + h_a} \quad (8)$$

$$C = -\frac{1}{h_0 + h_a} \frac{h_a - h_0}{6a\eta u_0} H$$

from which the excess of pressure:

$$p - H = -\frac{6a\eta u_0}{h_a - h_0} \left(-\frac{1}{h} + \frac{1}{h^2} \frac{h_0 h_a}{h_0 + h_a} + \frac{1}{h_0 + h_a} \right) \quad (9)$$

Knowing the excess of pressure in each straight section the carrying force for a section of width $y = 1$ can be computed

$$Z = \int_0^a (p - H) dx$$

taking h as independent variable and integrating between h_0 and h_a results in

$$Z = \frac{6a^2\eta u_0}{(h_a - h_0)^2} \left(\log \frac{h_a}{h_0} - 2 \frac{h_a - h_0}{h_a + h_0} \right) \quad (10)$$

or

$$Z = \frac{6\eta u_0}{\alpha} \left[+\frac{1}{\alpha} \log \frac{h_a}{h_0} - 2 \frac{a}{h_0 + h_a} \right] \quad (10a)$$

This formula, where the carrying force is proportional to the coefficient of viscosity η and to the relative speed u_0 , manifests in a simple manner that it is a phenomenon of purse viscosity. The geometric configuration of the oil wedge is also readily apparent.

(2) Equilibrium of oil wedge:

Let us now suppose that an external force parallel to axis ZO or load tends to bring the surfaces closer together, the slope α being regarded constant as well as the speed u_0 , by making

$$\frac{h_0}{\alpha a} = \lambda$$

the thrust can be written

$$Z = \frac{6\eta u_0}{\alpha^2} \left(\log \frac{\lambda + 1}{\lambda} - \frac{2}{2\lambda + 1} \right) \quad (11)$$

Figure 10 represents the variation of Z as function of λ ; Z decreases from infinity to zero while λ and with it h_0 increases from zero to infinity. At a given speed u_0 the load tends to make h_0 decrease; this decrease of h_0 causes the thrust Z to increase such that a stable equilibrium is established.

Now let us suppose that the equilibrium between thrust and load, this time regarded as constant, is established at every instant and that the speed u_0 varies, say from zero, for example (the case of starting).

Formula (11) gives then the relation between h_0 and u_0 reproduced in figure 11. It is seen that h_0 and u_0 increase simultaneously. Starting from contact at rest, the thickness of the oil wedge increases with speed.

From the beginning of motion, u_0 taking a small but finite value, the thrust is instantaneously sufficient to compensate the load no matter how high the latter may be, and hydrodynamic lubrication is established.

(3) Pressure distribution:

The pressure, equal to the atmospheric pressure at the two ends $x = 0$ and $x = a$, passes through a maximum for $h = h_m$ of the abscissa:

$$x_m = \frac{ah_0}{h_a + h_0} < \frac{a}{2}$$

The maximum pressure occurs therefore in the downstream half of the wedge. With respect to the two extremes of the wedge, the slope of the pressure distribution curve (fig. 12a) assumes the following values deduced from formula (6)

$$\left(\frac{dp}{dx}\right)_{x=0} = 6\eta u_0 \frac{h_a - h_0}{h_a + h_0} \frac{1}{h_0^2}$$

$$\left(\frac{dp}{dx}\right)_{x=a} = -6\eta u_0 \frac{h_a - h_0}{h_a + h_0} \frac{1}{h_a^2}$$

which indicates that the pressure increases slower at entry than it decreases at exit. The second derivative

$$\frac{d^2p}{dx^2} = 6\eta u_0 \frac{2h - 3h_m}{h^4}$$

indicates that the curve presents an inflection when $h = \frac{3}{2} h_m$, that is,

$$x = x_m \left(2 + \frac{h_0}{h_0 + h_a} \right)$$

which is only possible when $h_a > 2h_0$ and this inflection is produced for a value of x which limits the return flows, as will be shown later.

(4) Velocity distribution:

If the value of $\frac{dp}{dx}$ given by equation (6) is placed in expression (5) of u ,

$$u = u_0 \frac{z - h}{h} \left(1 - 3z \frac{h - h_m}{h^2} \right) \quad (12)$$

the parabola giving the variations of u as a function of z (fig. 12) can be plotted for each value of h kept constant. The direction of the concavity of the parabolas is given by the sign of

$$\frac{\partial^2 u}{\partial z^2} = -6u_0 \frac{h - h_m}{h^3}$$

For $h < h_m$ the concavity is turned toward the positive x ; for $h > h_m$ it is in the opposite sense, z being always smaller than h ; u and the expression in parentheses of formula (12) are of contrary signs.

Downstream from the maximum pressure $h < h_m$, u is always positive; the flow is always in the sense of displacement of the moving surface.

$\frac{\partial u}{\partial z} = 0$ for $z = 0$ when $h < \frac{3}{4} h_m$, which, like $h_0 < h$, assumes, after replacing h by h_0 and h_m by its value, that h_a is greater than $2h_0$.

It is then found that, in a straight section close to the exit nozzle, the absolute value of speed, which is equal to $-u_0$ at contact with the moving surface, increases as the distance from the moving surface increases, passes through a maximum and then decreases to zero at the fixed surface.

(5) Return current:

Consider, by way of contrast, what takes place in a section close to the inlet nozzle which is to have return flows, i.e., the flow in certain streamlines is in the opposite direction to that of the displacement of the mobile surface. In this case the quantity between the parentheses must be negative, i.e.

$$h > \frac{3}{2} h_m$$

Since $h < h_a$, it is necessary, by replacing h by h_a and h_m by its value, that

$$h_a > 2h_0$$

(6) Slope of oil wedge:

What is the best form to give to the wedge while the slope α is varied?

Taking as variable $t = \frac{\alpha a}{h_0}$ while $\frac{a}{h_0}$ is kept constant, the load capacity is expressed by

$$z = \frac{6\eta u_0 a^2}{h^2} \left[\frac{\log(1+t)}{t^2} - \frac{2}{t(2+t)} \right] \quad (13)$$

The study of this function (fig. 13) shows it to be zero for $t = 0$, to increase with t , pass through a maximum for $t_m = 1.2$, and then decrease asymptotically toward zero while t increases infinitely. There is an optimum slope of the wedge for a minimum oil film thickness h_0 .

(7) Effect of pressure upstream:

In the case of a pressure $H + P$ upstream from the wedge higher than the pressure H prevailing downstream from the wedge (obtained with the aid of appropriate pressure lubricating devices), the calculation shows that the thrust experiences an increase

$$\Delta Z = aP \frac{h_a}{h_a + h_0}$$

while without motion the thrust resulting from this pressure would be $\frac{aP}{2}$. There is therefore a slight increase in pressure due to the viscous flow. Since the pressure increase is slight and difficult to attain, further research into the very existence of pressure lubrication, whose object is to assure adequate oil feed by compensating for end leakage, is indicated.

7. Application of the Oil Wedge Theory

The theory is applied to the friction of axle guide bearings and piston rings or pistons of reciprocating engines, and in its general outlines also to the oil wedge formed between cylindrical surfaces of parallel axes such as the journal of a shaft turning on a journal bearing. Figure 14 shows the relative position of a heavy shaft and of the lower bearing on which it rests. The oil wedge results from the fact that the shaft has a smaller diameter than the bearing and that the shaft is laterally displaced, as shown in the figure.

In practice, allowance must be made for imperfect machining of the surfaces which is the reason that the contact between the two surfaces is established without the section being reduced to zero. Besides, the bushing is limited laterally and the flanges of the bearing are inadequate to prevent lateral leakage. Furthermore, the laws of flow can become complicated with the fatty oils which are apt to produce a stratified structure by stacking molecular layers. The liquid is then no longer isotropic and the coefficient of viscosity assumes a value that is considerably lower in the planes tangential to the molecular strata than perpendicular thereto.

As long as the molecules are not orientated, the chemical nature of the surfaces is not involved; as long as there is no contact between the

surfaces, their physical properties are not involved either. Whatever the degree of surface finish, the molecules of the liquid in contact with the surface have zero velocity. Oil circulation must be established to bring the oil from the exit nozzle to the inlet nozzle. The feed must be sufficient to compensate for end leakage and to carry away the heat generated in the oil by the viscous friction of the latter.

Oil baths are provided in the surfaces to bring the oil to the spots necessary for adequate feed of the oil wedge. The profile of these "basins" can contribute to the formation of the oil wedge. The geometrical configuration is so determined that the pressure balances the load. Brillie has developed this theory of relay "basins" and demonstrated various possibilities (filmatic bearing, Warlop bearing, etc.), when the ordinary oil grooves are prohibited.

Without going into further details about this theory of hydrodynamic lubrication which is outside the study of friction and wear, it simply is shown that this lubrication substitutes the internal friction of liquids for the friction between solids. The next step involves the examination of the limiting cases which occur either at start, while the solid surfaces are initially in contact, or under shock, while the oil can be expelled to the point where contact between metallic pieces is allowed.

(1) Coefficient of equivalent friction:

The resisting force X which is exerted on the moving surface of the oil wedge is the sum, integrated over the entire surface, of tangential stresses T_y produced by the viscosity in each element of the oil film in contact with this surface. For a section of width $y = 1$ this force is

$$X = \int_0^a y \left(\frac{\partial u}{\partial z} \right)_{z=0} dx \quad (14)$$

The value $\left(\frac{\partial u}{\partial z} \right)_{z=0}$ is obtained from equation (12) by taking the partial derivative of u with respect to z , then making $z = 0$. Introduction in equation (14) followed by integration gives

$$X = \eta u_0 \left[\frac{4}{\alpha} \log \frac{h_a}{h_0} - 6 \frac{a}{h_a + h_0} \right]$$

Generally expressed, the resisting force X for an oil wedge of any one form is equal to the product of viscosity by relative speed except for a form coefficient.

A coefficient of friction f can be defined such that the resisting force is fZ ; hence

$$f = k \frac{\eta u_o}{Z} \quad (15)$$

k being the form coefficient of the oil wedge.

(2) Effect of surface finish:

Consider a bearing supporting a constant load and measure at each speed u_o the resisting couple which permits calculation of the coefficient of friction f : plot $\frac{\eta u_o}{Z}$ on the abscissa and f on the ordinate (fig. 15). The result is a curve which has the straight line of equation (15) for an asymptote.

When the speed decreases, a value of $\frac{\eta u_o}{Z}$ is found for which, as a result of the surface roughness, the contact is established intermittently in some points; the coefficient f departs appreciably from the straight line and for values of $\frac{\eta u_o}{Z}$ even lower the coefficient f increases very abruptly up to the value of friction between solids in contact.

The minimum of $\frac{\eta u_o}{Z}$ is thus lower as the roughness of the surfaces decreases. It is of the order of 0.05 for a ground surface, 0.01 for a polished surface.

(3) Second limitation of application of superfinish:

Superfinish is of interest only to the extent when, in hydrodynamic lubrication, $\frac{\eta u_o}{Z}$ is lowered, that is, when the specific load P is increased so that minimum $\frac{\eta u_o}{Z}$ is approached.

In correctly designed machinery, the superfinish effects no improvements apart from the running-in period or in starting. In machinery of the future, it is hoped that superfinish will enable the use of much higher pressures, but two new difficulties present themselves:

(1) The operating conditions become more severe when $\frac{\eta u_o}{Z}$ decreases. Particular care must be used in the choice of the viscosity of the oil and to assure its constancy. It should also be noted that, regardless of the improvements effected in service, starting remains critical and is the principal cause of wear, as will be shown later.

(2) Experience indicates that between the superfinished surfaces in parallel friction, such as a shoe on a guide-block or piston rings on a steel cylinder, the oil does not penetrate between the surfaces because the oil wedge is nonexistent; moreover, the surfaces contact one another; seizing is inevitable. It is therefore necessary to restore the lubrication by grooves in the surface after the superfinish. The grooves provide spare oil and present no disadvantages since the carrying surface is reduced imperceptibly. In the case of gray cast iron, the cavities left by the graphite flakes are sufficient to maintain the lubrication of the superfinished surfaces; such surfaces require no grooves.

8. Establishment of the Steady State

M. Marcellin has determined the variations of the coefficient of friction as a function of the time for a bearing, the shaft of which starting from rest is driven at a uniformly accelerated motion.

Figures 16 and 17 give the speed as abscissa and the recorded coefficient of friction as ordinate. Two cases are to be considered according to whether the oil is mineral and inactive or fatty and composed of polar molecules.

(1) First case: mineral oil:

At rest, mineral oil is not opposed to contact between the metallic surfaces; the coefficient of dry friction and of rest is high (fig. 16). Set in motion, as a result of the low capillary tension and the spreading power resulting from it, the oil tends to penetrate between the surfaces, but by reason of the roughness there are intermittent and local contacts between the surfaces which produce partial seizing. The oil wedge is incompletely formed by reason of these irregularities and the oil film is unstable. The coefficient of friction is subjected to rapid oscillations of great amplitude.

As the speed increases, the coefficient of friction is reduced by a series of oscillations of decreasing amplitude, next the thickness of the correctly formed oil wedge is such that surface irregularities do not pierce it and the contact is prevented; the friction becomes low and stable. Above this speed the hydrodynamic lubrication causes a slow rise in the coefficient of friction proportional to the speed, as seen previously.

(2) Second case: fatty oil:

With fatty oils (fig. 17) the phenomenon is somewhat different. To the low capillary tension and the spreading there is added the property of absorption (adsorption) of the polar molecules.

As slight as the motion may be the surfaces are re-covered with a very rigid monomolecular film of fatty acid so that the coefficient of friction drops quickly to the value for greasy friction. It is only when the local pressures due to the roughness of the surfaces are extremely high that this film, although solidly adhering to the metallic surface, can be torn; the possibilities of seizing are less than in the preceding case, the oscillations fewer and smaller and soon cease altogether.

When the surfaces are well polished, immediately after the friction becomes stable, there is a gradual decrease of the coefficient of friction which arises from the progressive superposition of stratified layers of fatty substances which present easy sliding surfaces, as will be shown later.

When the speed continues to increase the thickness of the film becomes such that the polar molecules of the liquid mass are no longer orientated by the field of attraction emanating from the surfaces and the hydrodynamic lubrication takes the same course as in the case of pure mineral oils; the friction increases linearly with the relative speed.

(3) Conclusions:

It is seen that in practice the study of starting presents the greatest importance because it is at this time that the metallic surfaces can rub directly against each other with wear. These conditions can be minimized by polishing the surfaces, while the state of the surfaces is no longer involved once the hydrodynamic lubrication is established. The easier the oil is able to reach the surfaces and remain there, the quicker this complete lubrication is established. To the spreading due to the low capillary tension, there is added the adsorption of polar molecular layers, so that the fatty substances are recommended for reducing wear during the starting period.

The case of friction with reciprocal motions (guide blocks, pistons, piston rings, etc.) is another identical case; at every reversal of the direction of motion the speed is zero and the hydrodynamic lubrication is broken. The wear is produced at the start of the period of establishing the hydrodynamic state which follows every reversal of direction of motion.

9. Run-in

At excessive pressure and when the surfaces are rough, the projecting parts may contact each other momentarily. These zones of contact show a great temperature rise according to Hughes and the alteration of the oil due to the heat includes two effects in succession: rupture of the molecule giving unsaturated products, polymerization of the latter.

Although the remifications of the molecule can lead to light products by cracking, the nucleus of the molecule yields only heavier products by polymerization. Thus pyrolysis of the oil in imperfect lubrication with metallic contacts leads to very condensed products which form black deposits rich in carbon.

In the zones of the metallic contact there is rolling (flattening) with cold hardening, then tearing-out of metal. If the action is mild enough, the projecting parts are worn away little by little and the hydrodynamic action of the lubricant brings about a progressively lower pressure; the wear decreases; this is grinding; the oil is charged with metallic products of abrasion.

If, by way of contrast, the action is violent and if the released heat is such that the clearances shrink, the pressure increases; the tearing-out becomes more and more violent with formation of cavities or furrows. These furrows short-circuit the oil feed; the lubrication becomes worse; general seizure follows soon after.

To avoid this, it is recommended that one start with surfaces which have the best possible polish, use fatty oils during the grinding and adaptation period, and limit the load carried by the elements during this period to a value considerably below that carried later in normal service. The oil must be replaced afterward.

10. Shock Phenomena by F. Charron

Very high forces of short duration may exist in the mechanical organs, as is the case of the inertia forces in the reciprocal motion of a piston or of a force exerted on the piston of an engine at the moment of combustion.

Figure 18 shows by way of example the polar distribution of the force exerted on the wrist pin of a combustion engine during the 4 stroke cycle. The force results from the inertia forces from connecting rod rotation, the translation of connecting rod and piston, and the pressure exerted on the piston by the combustion chamber gases. It is fortunate that, owing to the spark advance at the start of the third cycle, the explosion pressure compensates some of the inertia effects, so that the highest stresses occur only between the fourth and the first cycle. In the chosen example which refers to an automobile engine, the maximum pressure on the bearing reaches 1.15 kilogram per millimeter².

It will not be the same if the compression is accompanied by detonation due to unstable peroxides formed during the start of the compression cycle. This explosion corresponds to a very violent shock and to an actual percussion force, the effects of which can be highly destructive.

Charron made a study of this shock phenomenon involved in hydrodynamic lubrication and arrived at the following conclusions reproduced here:

Visualize two flat, parallel disks of radius r_0 separated by a thin oil film of thickness h and viscosity η .

The system being initially at rest, a load Z is applied; it tends to expel the liquid radially between the two disks.

Let us suppose that this force is very great and is exerted during a very short period of time $t_1 t_2$ so that gravity and inertia forces during this interval could be disregarded.

A calculation similar to that of the oil wedge establishes that the viscous liquid, in being thinned from h_1 to h_2 under the effect of this percussion, offers an enormous resistance. This resistance offered by the film to the integral of the impulse force is given by the formula

$$\int_{t_1}^{t_2} Z \, dt = \frac{3\pi\eta r_0^4}{4} \left(\frac{1}{h_2^2} - \frac{1}{h_1^2} \right)$$

It shows that the resistance offered by the oil film increases indefinitely while the thickness approaches zero so that the oil film constitutes an effective protection.

The lubrication is perfect if at the end of interval t_2 the surfaces have not come in contact, that is, that h_2 is not zero.

It is seen further that this resistance is proportional to the fourth power of the homologous dimensions of the surface of the film. Consequently, it is not necessary to resort to great dimensions in order to assure perfect lubrication.

The resistance increases in proportion to the viscosity as in the case of the oil wedge so that the increase of viscosity is beneficial.

If, instead of assuming the viscosity constant, we take into account the increase in viscosity with the pressure

$$\eta = \eta_0 + a(p - p_0)$$

where η_0 is the viscosity under the ambient pressure p_0 , the calculation indicates that a much greater protection against shock is assured.

If the foregoing phenomenon is no longer exerted between two parallel flat surfaces, but on an oil wedge of which the inclined upper surface can move vertically downward under the effect of the pressure while the horizontal lower surface moves at a sliding speed u_0 , the calculation shows that the thrust due to the thinning of the oil film is, according to Charron's theory, additive to the Reynolds oil-wedge theory.

At low speeds and violent shocks such as those which occur in an automobile engine that knocks and whose speed decreases, the thrust due to the phenomenon of thinning is preponderant and the effect of the speed negligible. Conversely, at high speed of rotation where the forces of inertia balance the pressure force of the combustion gases, the thrust due to the effect of shock and the speed increase has a beneficial effect on the lubrication.

To make the thinning effect practical in service requires a minimum thickness h_2 without contact regardless of surface irregularities. Since the protection against shocks is so much greater as the film can become thinner it is of great interest to use polished surfaces. If the shock is such that, surface roughness being allowed for, metallic contact is established, fatty substances are recommended for opposing seizure by preventing the deteriorations of the surfaces, to assure softer friction, and lastly to speed the reestablishment of hydrodynamic lubrication which enables the reformed film to oppose the next shock. The influence of the surface of the film and of thinning favor the use of smooth, well polished bearings over roller bearings whenever the shaft is apt to be subjected to shocks.

11. Smectic State and Lubrication by Stratified Layers

The carbon atom can be represented (fig. 19) by a regular tetrahedron, the four vertexes of which represent the valences. In a simple carbon linkage the two tetrahedrons are joined by the vertex in such a way that the latter is on the line of the centers. In a three-carbon chain, the lines of the consecutive centers of gravity form an angle of $109^\circ 28'$ which is the angle of two medians of the regular tetrahedron. The distance between two adjacent centers of gravity is 1.54 \AA and the distance between three carbons is 2.54 \AA .

The long-chain hydrocarbons $\text{CH}_2 - \text{CH}_2 - \text{CH}_2 -$ of saturated fatty acids are arranged in zigzag fashion along this tetrahedral scheme. When two chains are placed side by side, the difference between them is of the order of 3.7 \AA .

The crystalline network of pure solid stearic acid is shown in figure 20; the network consists of four molecules; the system is monoclinic and has

$$a = 5.546 \text{ \AA} \quad b = 7.381 \text{ \AA} \quad c = 48.84 \text{ \AA}$$

for parameters.

Oleate of solid sodium has a network of 43.4 \AA (Broglie and Friedel) corresponding to a double layer, because only the regions of high density are diffracting layers; in this double layer or plate, the molecules of a single molecular layer have all their active groups turned to one side and the two layers of one plate are joined by the faces containing these active groups. The free ends of a layer are formed by the ends CH_3 of fatty chains.

Grandjean investigated the passage from the solid to the liquid state of ammonium oleate and concluded that in the most general case starting from the crystalline solid state at temperature T_1 the body assumes the pasty smectic state, greasy, uniaxial, positive; 15 or so double layers are easily obtained in which the fatty chains are arranged perpendicular to the cleavage planes. At a higher temperature T_2 the cleavage planes and the planes of optical refractivity disappear, but the parallel orientation of the molecules continues; it is the nematic mesomorphic phase of the liquid state. At a still higher temperature T_3 the body assumes the isotropic liquid state.

The change from the crystalline solid state to the isotropic liquid state comprises two intermediate anisotropic states where the degree of symmetry and the order decreases. Depending upon the bodies, the two states, one of the two, or none may exist; hence, four possible cases in all.

When the smectic state arises from the crystallized solid or from the nematic state, the orientation is already fixed, but when it originates from the isotropic liquid state, the source which orients the smectic phase and permits its formation must be identified.

This source can be the viscous flow when the latter is applied to a very thin liquid film for which the size of the molecules is not negligible. The flow of a fatty acid in a capillary tube involves the orientation of molecules in stratified layers and the viscosity thus ascertained is different from that of a weighty mass of liquid in which the molecules have irregular positions and orientations.

The effect of the pressure is manifest on methyl stearate which gives one molecule per network when it is obtained by fusion and two molecules end to end when obtained by pressure of crystalline flakes. This orientation, under the effect of the pressure with formation of planes of easy slip, is the simple definition of the oiliness of fatty liquids in the common sense of the word.

This orientation can also appear by imperfect epitaxis (arrangement) from the surface of crystalline solids. Manguin and Grandjean have shown that liquid azoxyanisole orientates itself very easily on a fresh cleavage of muscovite mica. (The optical axis of the smectic liquid coincides with a reticular row forming 30° with the track of the symmetry plane 010. This shows that this plane is not a true plane of symmetry but a translatory plane of symmetry.) Melted para-azoxycinnamate of ethyl also is orientated on a cleavage of talc or orpiment. (The optical axis of the smectic body is oriented parallel to a well-defined direction, comprising the cleavage plane, the droplet flows very rapidly in a direction perpendicular to the axis and very slowly in the direction of the axis so that it assumes the shape of a thin birefringent liquid rod with perfectly straight edges.) This phenomenon of orientation is general; Trillat has shown the orienting of fatty glycerides on metallic surfaces. The orientation of fatty acids on metallic surfaces presents a great rigidity which is put to benefit in greasy lubrication, as will be shown later.

In arriving at the steady state of hydrodynamic lubrication with fatty oils starting from rest, the molecules are progressively oriented under the action of the flow and the pressure and, starting with surfaces having a monomolecular layer of fatty acid, yield more and more stratified layers until the distance between the surfaces is such that hydrodynamic lubrication takes place; the orienting forces make themselves felt much less as the surfaces are farther apart and the flow is more turbulent.

Layer lubrication is thus an uncertain intermediate between hydrodynamic lubrication and greasy lubrication at which we shall arrive.

CHAPTER 3

GREASY (BOUNDARY) FRICTION

We have just defined the oiliness of fatty acids and shown that it appears as a result of the formation of stratified layers sliding easily over each other. In the present case, greasy (or boundary) friction is defined as that which does not permit the obtainment of the hydrodynamic state as a result of high pressure, low speed, and low viscosity but which nevertheless yields a low and stable coefficient of friction due to the existence of adsorbed monomolecular layers of lubricant on the surfaces.

The thickness of a double layer of stearic chains being of the order of 46 \AA and the forces of atomic attraction being effective only over a distance of a few angstroms, this greasy double layer is sufficient to remove one of the metallic surfaces from the field of attraction of the other and replace the friction between solids by sliding between fatty layers.

In greasy friction, the contact between two metallic surfaces is avoided by the formation on each of the surfaces of fatty monomolecular layers of lubricant which must be strongly adhesive and very rigid in order to resist the high pressures.

The study of greasy friction that follows refers to the author's own experiments made in 1934 to 1936, which have not been published. It is only recently that we became aware of the work of Bowden and Leben on the same subject; these results are in agreement with our own tests.

12. Use of Herschel's Apparatus

The 1934-1936 tests were made with the Herschel apparatus represented in figures 21 and 22. It consists of a vertical shaft, a horizontal plate set in very slow and uniform motion of rotation by a wormgear, and an electric motor; resting on the plate is a set of three balls in an aluminum mounting; the mounting consists of two bearings (jewels) in which are inserted two knife edges whose vertical edges parallel to the axis are linked to a compensating device capable of opposing the rotation of the set of balls with the lower plate. This compensating mechanism includes, besides the two aforementioned knife edges,

- (a) A system of spiral dynamometer springs
- (b) A drum with two guide pulleys and two plates for calibrating the springs

- (c) A cylindrical oil damper making the system aperiodic
- (d) A pointer and dial for reading the torque,
- (e) and lastly, an adjustable stop for breaking the adhesion forces in case of seizing

It is to be noted that in this apparatus a ball does not rest on a plane by a geometrical point of contact; owing to the elastic deformations, the contact is made along a circle. The latter being small, the pressure is very high, the total weight including the three balls and their mounting is 30g with steel balls 10 millimeters in diameter. Assuming a plate of red copper, the application of the Hertz formula gives a radius of 0.017 millimeters, a mean pressure of 34 kilograms per millimeter² and a maximum pressure of 51 kilograms per millimeter².

The operation of the setup is as follows:

Starting from rest, the set of three balls is carried along with the rotatory motion of the plate. The dynamometer springs are compressed until they exert a couple including the force of friction of the balls on the plate. From this moment on, the plate continues to turn without carrying the movable equipment; a relative motion therefore exists between the balls and the plate. As the coefficient of friction is lower in motion than at rest, the springs expand and the set of three balls move in a direction opposite to that of the preceding. Two cases may present themselves:

- (1) If greasy oil has been inserted between the set of three balls and the plate, the compensating springs expand, the three balls turn back to the position of equilibrium corresponding to the friction in motion of the balls on the plate (fig. 23).

If C is the compensating torque read on the dial, $3P$ the weight of the set of three balls, R the distance of the center of the contact circle of a ball from the axis of the apparatus, the coefficient of friction is

$$F = \frac{C}{3PR}$$

- (2) In the absence of oily fat substances and the impossibility of obtaining hydrodynamic lubrication by reason of high-pressure, low speed and low viscosity, it is found that, at the moment where the moving equipment turns backward, the surfaces come in contact since a stable film is impossible. The surfaces are welded together and the balls are again carried along by the rotation of the plate until the compensating couple

balances the forces which make the balls stick to the plate. At this moment, the moving system stops and the balls resume a relative motion with respect to the plate. This phenomenon begins again indefinitely by a series of oscillations.

The use of the Herschel apparatus calls for absolutely perfect cleanliness of the surfaces to be tested; they must be polished micrographically (they present then the amorphous Beilby layer), or electrolytically (if a crystalline structure is desired). Degreasing of the balls and the plate must be complete and all surface contamination by impurities must be avoided. Polishing is done advantageously by chrome green added to the oil that is to be studied. Precautions must also be taken to assure perfectly dry surfaces because the layer of water vapor adsorbed by the surfaces has a particular affinity for fatty acids. This drying can be obtained by dipping the balls and the plate in boiling benzene which distills the azeotrope benzene-water. The balls and the plate, thus prepared, must be kept under vacuum and in the presence of phosphoric anhydride.

(1) Effect of concentration in stearic acid:

Herschel's apparatus can be used for studying the effect of different additions of fatty acids to mineral oils; or the mineral oil can be replaced by other organic liquids such as oil of vaseline or tetralin, judged preferable for experimentation, because they are better defined, or pure bodies, low volatility at low viscosity, etc., and, in any case, good solvents for additives.

Wells and Southcombe made a study of the concentration of stearic acid; figure 24 shows that, in the absence of stearic acid, the coefficient of friction is unstable and increases continuously; it requires but a 0.001-percent addition of fatty acid to cause the coefficient to drop and become stable for a relatively short period of the order of 5 minutes. With an amount ten times greater, the coefficient drops and remains stable for about 10 minutes or so. With a 0.1-percent addition, the coefficient of friction assumes and maintains a constant value of 0.075 no matter what the duration of the test may be. When the stearic acid concentration is increased above this value, the improvement in the coefficient of friction becomes independent of the concentration.

(2) Effect of length of the fatty chain:

Table III gives the coefficient of friction for additions of several fatty acids.

TABLE III.- PROPERTIES OF DIFFERENT FATTY ACIDS

Caprylic acid	C ⁸	f = 0.160	unstable
Lauric acid	C ¹⁰	0.080	stable
Palmitic acid	C ¹⁶	0.065	
Stearic acid	C ¹⁸	0.062	
Behenic acid	C ²²	0.072	

It is readily seen that the length of the chain must reach 10 atoms of C before the friction becomes low and stable. Above 16 atoms of C the improvement due to increased length of chain is negligible; it is the length necessary and sufficient so that the metal of one surface is free of the influence of the other.

13. Changes Due to Corrosion

Figure 25 shows the coefficient of friction as function of the time with the Herschel apparatus and with steel balls and cadmium plate, the lubricant consisting of vaseline oil containing 1 percent of stearic acid.

Curve 1 refers to a test at 30° C; the coefficient of friction is low and stable.

Curve 2 carried out consecutively at 70° C temperature shows a stable but considerably lower coefficient of friction.

Curve 3 carried out consecutively at 100° C shows, at first, a drop in the coefficient to the extremely low value of 0.035 followed by a progressive rise with time.

Test 4 was repeated at 30° C; the friction remains just as high as at 100° and continues to increase, but after a little while it becomes unstable, which indicates rupture of the fatty film.

For test 5, the plate was washed with new oil; the friction is low and stable which proves that the plate has not been altered.

After tests 1, 2, and 3, the used oil was withdrawn with a pipette; the plates polished, and the used oil put in place again; the result was curve 6; the friction is very high and unstable from the start indicating that the used oil has lost its properties.

(1) Effect of hydrolysis:

In the results of figure 26, which were obtained also with a cadmium plate, tests 1 and 2 refer to vaseline oil; the friction is high and unstable.

Tests 3, 4, and 5 refer to vaseline oil with 1-percent stearic acid added; the friction is low and stable.

In tests 6 and 7, the vaseline oil with 1-percent stearic acid had previously been made to react with cadmium shavings for 4 hours at 120°. The result is a depleted oil; the friction is high and unstable; these results refer to perfectly dried cadmium plates.

Test 8, by way of contrast, refers to a cadmium plate on which the humidity adsorbed by its surface had not been removed. The friction is slightly lower but still unstable.

The procedure for test 11 was as follows: The vaseline oil with 1-percent stearic acid added was made to react with cadmium shavings for 4 hours at 120°; to the thus changed oil is added a small amount of water at 100° C during 2 hours. The friction is stable and still lower than in the preceding test.

Tests 9 and 10 are tests intended to show the effect of reincorporating fatty acid in the changed oil.

The result of these experiments is that the attack of cadmium by stearic acid forming a soap causes the stearic acid to disappear and the oil loses its properties. On the other hand, the cadmium soap formed by this attack has no inherent oily property, but is hydrolyzable in regenerating fatty acid. The water necessary for the hydrolysis can be introduced deliberately (test 11) or can consist of the water vapor adsorbed by the metal surface (test 8).

(2) Effect of time and temperature:

Figure 27 represents three typical cases of the effects of time and temperature, acting to modify the lubrication phenomenon.

The curve at the left refers to a cadmium plate and indicates the disappearance of the fatty acid from the lubricant following chemical reaction on cadmium when the temperature reaches 100° C.

The curve in the center refers to a plate of copper at 20° C; the friction is stable; it is no longer the same at 70° C as a result of the dissolution of the copper soap formed at the surface of the metal.

The curve on the right presents a rather unusual phenomenon to the extent that at ordinary temperature, the stearate of lead gives a stable coefficient of friction. At 70° or 100° temperature there is, first, a rise in friction accompanied by instability and blackening of the liquid, then low and stable friction. The phenomenon is due to the thermal decomposition of the stearate of lead to stearone and colloidal lead; the oiliness is thus due to the fine particles of colloidal lead. It is assumed that they are rolled between the rubbing parts and prevent seizure in the manner of colloidal graphite.

14. Saturation Effect

Table IV gives, for several metals, the coefficient of friction of an organic liquid treated with stearic acid or oleic acid.

TABLE IV.- SATURATION EFFECT

STEEL BALLS, TETALIN WITH 1-PERCENT FATTY ACID ADDED

Plate	Stearic acid	Oleic acid
Cu	f = 0.09 stable friction	f = 0.200 friction unstable, soap very soluble
Mg	0.072 stable friction	0.094
Cd	0.060 stable friction	0.125
Zn	0.050 stable friction	0.102

} friction stable

There is no possibility of obtaining oiliness with oleic acid in the case of copper, the oleate of copper being very soluble.

On the other hand, the oleic acid chain, being convertible at its center at the level of the double carbon bend (Woog), has a length half

that of the saturated stearic acid; the coefficients of friction are much higher. While stearic acid is favorable to greasy lubrication, oleic acid is not.

15. Noble Metals and Reactive Metals

The balls and plates can be made of glass, fused quartz, or platinum, i.e., any material that resists the chemical action of stearic acid. The coefficient of friction departs from a value greater than 0.35 at the end of 30 minutes by being continuously unstable. On the other hand, metals attacked by stearic acid such as silver, copper, or cadmium, give a stable coefficient of friction and decrease with time to a stable value of 0.1 percent (fig. 28).

Classification of Metals According to Reactivity:

Tables V and VI give the classification of several metals used for making the plates.

TABLE V.- CLASSIFICATION OF METALS
ACCORDING TO REACTIVITY

Quartz Balls, Tetralin Plus 1 Percent Stearic Acid	
Plate: Fe	$f = 0.103$
Cu	0.09
Mg	0.07
Cd	0.06

TABLE VI.- CLASSIFICATION OF METALS
ACCORDING TO REACTIVITY

Steel Balls, Tetralin Plus 0.2-Percent Stearic Acid	
Plate: Fe	$f = 0.140$
Sn	0.133
Pb	0.130
Ag	0.105
Al	0.098
Cu	0.093
Mg	0.092
Cd	0.082
Zn	0.075

The classification of table VI is the same as in table V. It was obtained with a solution of 0.2-percent stearic acid and tetralin; castor oil gives an identical classification. The metals are classified according to their capacity to react on fatty acids, not according to their electrochemical potential compared to that of hydrogen. The distinct superiority of cadmium justifies the use of cadmium-base alloys or cadmium plating of gears for the running-in period, provided, however, that the lubricant is made greasy.

16. Metallic Couples

We have determined the coefficient of friction given by solutions of 1-percent stearic acid on metallic surfaces of silver, cadmium or cadmium alloys with 5 percent Ag forming a solid heterogeneous solution in the rough-cast state or else of cadmium surfaces silvered by displacement. In the last case, the silver coating is known to be porous so that the silver and the cadmium are reciprocally in contact with the wetting liquid. The coefficients of friction are as follows:

TABLE VII.- METALLIC COUPLES

Steel Balls, 1-Percent Stearic Acid in Tetralin	
Ag	$f = 0.106$
Cd	0.073
Cd alloy with 5 percent heterogeneous Ag	0.067
Cd silvered by displacement	0.056

The heterogeneity of cast Cd-Ag alloys improves the coefficient of friction considerably, as well as the deposit of silver on the cadmium surface. These experiments are evidence of the beneficial effect of electrochemical couples on the formation of oily films.

Copper stearate:

The results of friction measurements on plates of various metals, the lubricant containing 1 percent of copper stearate, are given in table VIII.

TABLE VIII.- MUTUAL DISPLACEMENTS - COPPER STEARATE

Steel Balls, 1-Percent Copper Stearate in Vaseline Oil			
Plate: Cu	$f = 0.170$	} unstable	
Sn	0.145		
Ag	0.125		
Fe	0.105	} transition	
Mg	0.08	} mutual displacement of Cu stable and oily	
Zn	0.07		
Pb	0.058		
Cd	0.055		

The coefficient of friction is low only in the case where there is mutual displacement with precipitation of copper. Stability of friction and oiliness are the result of the formation "in situ" of soap of the rubbing surface metal.

17. Esters

Table IX gives the results obtained with different esters by resorting to perfectly dried balls and plates or, by way of contrast, to balls and plates of which the surfaces have adsorbed water vapor.

TABLE IX.- ACTION OF VARIOUS ESTERS

Coefficient of friction (α unstable, = stable)		
	Anhydrous medium	Wet medium
Tristearin (Glycerol, tristearate)	0.2 α	0.10 =
Methyl stearate	0.18 α	0.070 =
Stearyl acetate	0.15 α	0.15 α

The fatty esters always give high and unstable friction in the anhydrous mediums, while in the presence of wet surfaces the esters of long-chain fatty acid yield low and stable friction. The explanation lies in the hydrolysis of the ester with formation of fatty acid.

Other Organic Bodies:

(a) Stearamide: The long-chain fatty stearamides, which have $R\text{-CONH}^2$ as functional grouping, have a hydrogen easily replaceable by a metal. With an extremely weak dose, they are likely to give a low and stable coefficient of friction with perfectly dry metallic surfaces the same as fatty acids.

(b) Alcohols: The fatty alcohols even with long chain are devoid of all oiliness; the coefficient of friction is high and unstable.

(c) Ammonium stearate. Urea stearate: These salts are susceptible to dissociation when hot by releasing the fatty acid; they also present, when hot, a marked oiliness by giving a low and stable coefficient of friction.

(d) Alumina stearate: The easy hydrolysis of alumina stearate makes it possible to obtain an appropriate oiliness in the presence of a trace of water as, for example, when the metal surfaces have not been particularly dried, so this soap is utilized very extensively in lubricants for drawing and wire drawing. In this case, the water contained in the lubricant gives by hydrolysis an alumina gel hydrated to the consistency of vaseline.

18. Different Fatty Acids

Table X shows, for steel balls and copper plates, the classification of the coefficient of friction obtained from several natural fatty acids in 5-percent concentration. The friction is low and stable only in the case where there is obviously a release of fatty acid and where the latter is able to react on the rubbing metal surface.

TABLE X.- FATTY ACIDS

5 Percent in Tetralin	Coefficient of Friction	Observations
Methyl stearate Methyl behenate Ammonium stearate Urea stearate Ethyl stearate	$f = 0.060$ 0.062 0.072 0.075 0.080	Persistent stability and great oiliness
Cetyl palmitate Tristearin Tallow	0.085 0.095 0.102	Precarious stability
Stearic alcohol Coconut butter Lard oil Lanolin Cetyl alcohol Oleic alcohol Stearyl acetate Nothing	0.115 0.115 0.115 0.120 0.125 0.135 0.160 0.160	Increasing instability

19. Compounding of Lubricating Oils

Greasy friction as defined in the foregoing consists essentially in the action of the fatty acid which can be diluted in a mineral oil and

which reacts with the metal surface. This corrosion stops as soon as the soap layer is formed if the latter is insoluble, adhesive, and continuous; however, the maximum mechanical stresses can break it up locally and then it is reformed almost instantaneously. This breakdown entails a loss of metal in the form of soap, which is one of the forms of wear. The amount of stearic acid necessary at each instant is very small but on account of the corrosion in service, it is spent quickly. Since its solubility in mineral oils is not very great and also in order to avoid the premature corrosion which would result from an abnormally strong concentration, it is of advantage to compound the mineral oil by adding esters or salts of more soluble and noncorrosive organic basis such as methyl stearate or triethanolamin stearate which, in service, release stearic acid progressively by hydrolysis or by thermal dissociation without the amount of acid ever becoming very great. The compounded oils assure hydrodynamic lubrication because of their properly chosen viscosity, and greasy friction is of benefit during the running-in period of a new machine or during each starting period.

20. Hypothesis of the Mode of Action of Fatty Acids

The long-chain fatty acids exhibit a strong adhesion to the metal surface so that the monomolecular film thus formed is not broken under conditions of friction which destroy the films given by the adsorption of other types of polar molecules. This adhesion is obviously due to the chemical affinity of acids to the metal but not much is known about the intimate structure of this adhesion. If it is supposed that a single fatty chain is attached to an atom of bivalent metal, the latter preserves a positive electric charge of the kind to keep it near to the place which it occupies in the crystalline system and it is apparent that the adhesion of the film, thus formed, of electrostatic nature, is very solid. If, on the other hand, two fatty chains were hooked to the same bivalent metallic atom, the soap formed would no longer have a free electric charge and it would be subjected only to the much weaker forces of attraction of the polar molecules.

As regards the hydrogen ion of the fatty acid released by the reaction with the metal, it is easily visualized that it could, by reason of its small volume, be lodged in the empty spaces of the first reticular layer, its positive electric charge compensating for that lost by the metal. The free displacement of the valence electrons is not disturbed. This is the usual mechanism of the adsorption of hydrogen by metal surfaces in the attack of a metal by an acid.

For the fatty oil film to be formed with the same density as in the crystallized stearic acid, it would be necessary, by epitaxis, to bring the nodes of its system (parameters $a = 5.546 \text{ \AA}$ and $b = 7.381 \text{ \AA}$) into

coincidence with the nodes of the crystalline system of the metal surface. For alpha iron of face-centered cubic structure, $a = 2.87$, so that $2a = 5.74$ and $3a = 8.61$ which are, respectively, 4 percent and 15 percent more than the parameters of stearic acid. For copper of face-centered cubic structure, $a = 3.609 \text{ \AA}$, so that the diagonal $a\sqrt{2} = 5.09 \text{ \AA}$ and $2a = 7.218 \text{ \AA}$ represent, respectively, 9 percent and 2.3 percent less than the stearic acid parameters. In these two examples, the epitaxis introduces a substantial distortion of the crystalline system of stearic acid. Is it possible that the adhesion of fatty chains is made according to the laws of chance? The examination of the surface by electron diffraction should afford a solution.

21. Rolling Contact Bearings

These bearings are based on the principle of rolling friction. We will examine separately the case of ball bearings and roller bearings where the role of lubrication is reduced to its simplest form and the case of needle bearings which utilize hydrodynamic lubrication.

(1) Ball bearings or roller bearings:

The principle of ball bearings or roller bearings is to substitute, for the sliding friction of a smooth bearing, rolling friction which is infinitely smaller.

Consider, for example, a bearing with eight balls of 2.775 millimeter radius and an inner ring with a toroidal groove of 3.05 and -9.86 millimeter principal radius of curvature. The maximum load capacity in normal service is 750 kilograms. By the Hertz formula, the average pressure is 1180 kilograms per millimeter² and the maximum pressure is 1780 kilograms per millimeter². These pressures are enormous.

Experience indicates that in normal conditions of operation and speed of rotation, a bearing without lubrication does not last, the hard steel becomes soft, and the balls break violently.

M. Caquot remarked that the balls are able to resist the external forces to which they are subjected in service only when the outside layers are under strong compression.

Actually, during the brisk hardening of the balls the outside layers are cooled first and become martensitic, very hard, tough and indeformable (retain their shape). As a result, the inner layers can no longer contract freely and are put under triaxial stress producing a considerable compression, largely hydrostatic, in the outside layers. In such a case

the core is very fragile, the peripheral layers, on the other hand, offer a resistance to decohesion and an enormous endurance to repeated stresses.

In service and in the absence of lubrication the instantaneous local heating causes a softening of the hardened steel, due to reheating, and the disappearance of internal stresses. This change needs no more than an incipient crack to make the hard steel ball burst as a result of the extreme fragility of the core under triaxial stress.

The remedy is the use of rollers of carburized steel. Having a low carbon content the core can be stretched by rapid tempering without becoming fragile. In the absence of lubrication, the carburized rollers become soft, then become progressively deformed plastically but without rupture.

To assure satisfactory functioning of ball rollers, they must be lubricated and, because of the high pressure, the use of fibrous, oily lubricant with a thick mineral oil base treated with aluminum stearate is recommended.

Owing to the low surface tension, the lubricant spreads well over the surface and, because of its oiliness, is strongly adhesive. Moreover, the pressure on a well-greased ball surface element in contact with the ring increases very rapidly, reaches a high value for a very short time, and then decreases again. These are the conditions of lubrication under shock (loading) studied by Charron. The oil is not expelled completely; if the balls are perfectly polished, there remains an infinitely thin film opposing the contact. There is no alteration of metal.

(2) Needle bearings:

The principle of the needle bearing is entirely different. It may be considered as a smooth bearing with large clearance between the shaft and the concentric ring and forming a thick oil film in which the needles are bathed.

The oil moves with a rotatory motion about the shaft. The layer in contact with the shaft turns at shaft speed while the outside layer in contact with the fixed ring remains stationary. The oil, through its viscosity, carries the needles in a rotatory motion about themselves and at the same time in a translatory motion about the shaft. The oil is rolled between the shaft and the needles without being decelerated by the latter. The speed distribution near the axis is little modified by the presence of the needles while the radial clearance between the outer ring and the shaft is reduced by the needles diameter. On the other hand, the oil film inserted between the shaft and the needles or between the needles and the outer ring assures a very uniform pressure distribution

so that hard steel and high loads can be used. This hydrodynamic lubrication presumes that the end leakage parallel to the axis is small which implies that the length/diameter ratio of the needles is great and that the needles are almost in contact.

Lastly, at starting or in case of overloading for which the conditions of hydrodynamic lubrication are not satisfied, the needles come between shaft and ring to prevent sliding friction by replacing it with rolling friction which is infinitely lower.

In practice, the action is a little more complex inasmuch as stroboscopic examination shows that the needles have an irregular movement; sometimes they turn, at other times they do not. In the latter case, the needles lie on the outer surface as a result of the slow rate of flow of oil between the needles and the ring. Thus they form a series of oil wedges around the shaft which assures good hydrodynamic lubrication.

The needle bearing is therefore an intermediary mechanism between ball bearings and smooth bearings with hydrodynamic lubrication combining, in a certain measure, the advantages of both while avoiding their respective faults.

CHAPTER 4

SEIZURE

Seizure is the welding of two rubbing metal surfaces through pressure or heat at contact. This welding indicates that the surfaces approach to a distance less than or equal to 2 or 3 Å.

22. Mechanism of Welding by Comparison

Consider two solid bodies pressed against each other. Owing to the geometrical shape and the roughness of the surface, the contact is generally established over very small areas which are elastically deformed. Over the extent of these very small contact areas, the atoms of these bodies approach each other within very small distances of the order of 2 to 3 Å in which the forces of attraction are exerted. Nevertheless, the actual area of contact being infinitely small, the adhesion of the bodies to one another is negligible.

When the force of pressure is increased, two cases must be considered:

(1) The materials are plastic such as fuller's earth or hard rubber. In this case, the deformation assures a large area of contact and the adhesion is high.

(2) The materials are hard and fragile such as baked clay or bakelite. In this case, there are created, near the strongly elastically compressed contact zone, zones of elongation where the breakdown is produced. The material crumbles.

The metallic character is characterized by a compact crystalline structure with high degree of symmetry (face-centered cubic, compact hexagone, centered cubic) and the common sharing of valence electrons. Metals and alloys are, in addition, microcrystalline aggregates with fine boundaries, hence, possess very strong cohesion and great plasticity. By way of contrast, the binary metal metalloid compounds are characterized by the fact that the distances between the atoms of adjacent molecules of the same crystal are considerably greater than the distances between the atoms of the same molecule. Besides, the valence electrons placed in common between the atoms of the same molecule gravitate about the latter without being dispersed in the remainder of the crystalline system. Owing to this fact, the structure offers neither the same compactness nor the same homogeneity as in the preceding case (for metals

and alloys) and the degree of crystalline symmetry is frequently much lower. Moreover, the crystals often have large distances between them. The material is nondeformable and is fragile.

The welding through approach of the surfaces is therefore a property characteristic of the metallic state of which the binary metal-metalloidal compounds are entirely devoid. Welding is facilitated by the increase of pressure and temperature which increases the plasticity.

As regards the contact between two different metals, the welding tendency is considerably improved if there is a possibility of interpenetration, that is, if, under the action of the thermal agitation, the atoms of both metals are capable of exchanging their positions. The metals which exhibit mutual filiations give much stronger welds because the variation of the properties is progressive at passage from one body to the other. As a result, seizure is much less likely in friction between two totally different metals without filiation.

As regards contact between binary compounds (metal-metalloid), the latter being nondeformable and fragile and of substantially different structure from the metallic state, welding and filiation are not possible. To prevent welding and filiation and hence seizing between rubbing metal surfaces, it is sufficient to form a binary metal-metalloid compound by superficial chemical reaction.

23. Mechanism of Seizure

In the Amsler or the SAE wear testing machine, two cylindrical rollers with parallel axes are brought in contact with one another under high pressure and rotated at different speeds, producing sliding.

If the friction couple measurements are recorded as a function of time under high speed and pressure on an Amsler machine, two cases must be considered: The case where the conditions of lubrication are satisfied and friction stabilizes at a low and constant value, and the case where friction remains high and continuously subjected to irregular and violent oscillations. In the latter case, there is seizure.

The mechanism of seizure is as follows: The pressure expels all the interstitial liquid; the friction, with direct contact between the two metal surfaces, causes considerable local heat initiating welding and filiation of the rubbing surfaces. The motion stops as a result of the inertia of the pieces; hence a shock. This shock induces a shear which is produced in the most fragile zone. If the crystalline metals are mechanically polished, that is, have a Beilby layer on the surface, which itself is particularly fragile, the tear extends across the entire depth of the Beilby layer to the crystalline sublayer. If the surfaces

are covered by metal-metalloid compounds by a process to be described hereinafter, the break occurs without great forces in this layer of metal-metalloid compound of very low resistance to welding.

The alternations of heating through friction, cohesion and filiation, shock and shear are renewed indefinitely by producing the oscillations of the couple as recorded in figure 30. These are the phenomena of seizure; this seizure is accompanied by tearing-out of material, this is, high wear with great alteration of the rubbing surfaces.

24. Measurement of the Coefficient of Friction under High Pressure

In the tests on the Amsler machine, the friction is deduced from the couple exerted on the motor shaft and measured by means of a pendulum dynamometer. Boerlage also made a study of friction under extreme pressure apt to induce seizure when the speed is higher, but he employed an apparatus different from that for seizure itself; this apparatus, (fig. 29) is composed essentially of three balls fixed in horizontal position and locked in a cup for receiving a lubricant and a moving unit consisting of a set of heavy weights and a ball through whose center passes the vertical axis of the ellipsoid of inertia. The ball of the moving unit rests on the base formed by the three stationary balls; considerable contact pressure is therefore developed. After starting the moving unit to rotate about its vertical axis, the circles of elastic contact on the three balls are very small and fixed; on the rotating ball the contacts sweep a narrow spherical zone. The mean coefficient of friction is derived from the time of rotation between the initial constant speed and complete stoppage.

25. Extreme Pressure Lubricants

(1) Amsler wear tests:

At pressures below 50 kilograms per millimeter², the coefficient of friction is low and stable (curve 1, fig. 30) when the rollers are lubricated with mineral oil treated with stearic acid, graphite, or colloidal lead. Pure mineral oil gives a high coefficient of friction with violent oscillations characteristic of seizure (curve 2, fig. 30).

At pressures of from 50 to 100 kilograms per millimeter², sulphurized oil (fatty oil and flower of sulphur) or soluble sulphurized cutting oil or colloidal sulphur in suspension in water give a low and stable friction free from seizure. A good liquid for preventing seizure is obtained by taking water whose viscosity has been increased by adding glycerin or gum and whose sulphurant action is obtained by colloidal sulphur which can be obtained in situ by decomposition of hyposulfite of soda by hydrochloric acid.

For pressures of from 50 to 100 kilograms per millimeter² and at sliding speeds still attainable with the Amsler machine, pure mineral oil treated with stearic acid, graphite, or lead is unable to prevent seizure which is characterised by high friction coefficient, violent oscillations of the friction coefficient, knocks in the machine and tearing-out of material from the rollers.

At extreme pressures of the order of 100 to 200 kilograms per millimeter², oil treated with 1 percent sulphur monochloride S_2Cl_2 or better yet 1 percent of very active phosphorus trichloride PCl_3 must be used.

One sees that liquids resist seizure better by a vigorous reaction with the metal, giving rise to formation of sulfur, chlorine or phosphorous (compounds).

TABLE XI.- TESTS ON THE AMSLER MACHINE

Pressure (kg/mm ²)	Type 1	Type 2
≤ 50	Mineral oil + 1 percent stearic acid Mineral oil + graphite Mineral oil + colloidal Pb	Pure mineral oil
$50 < P < 100$	Sulfurated oil or soluble sulfurated oil or water + colloidal S	Mineral oil + 1 percent stearic acid or graphite or lead
Extreme $100 < P < 200$	Oil + S_2Cl_2 1 percent Oil + PCl_3 1 percent	Sulfurated oil

(2) Boerlage's experiments:

In a different setup (figs. 31 and 32) specifically designed for studying seizure, Boerlage used the same four ball arrangement as in the friction measurement but with the difference that the upper ball integral with the flywheel is rotated at high speeds by an electric motor, while the cup which contains the three bottom balls is linked with a damper and a dynamometer including a small stylus recording the couple developed on a drum driven at uniform speed of rotation by a

clock mechanism. The force of contact is obtained by weights and a lever acting at the axis of the cup from below.

Under the very heavy loads and the high speeds employed, the seizure is very representative. It appears in the form of very strong welding of the moving ball to the three stationary balls (fig. 31(a)) to such a point that rotation is suddenly and definitely stopped since the forces of inertia are unable to shear the weld.

Boerlage operates with a liquid lubricant, a specific load, and speed and observes the time lapse at the end of which there is violent seizure and stoppage (fig. 33).

The tests disclose a certain amount of dispersion; for a small load the time lapse may vary from 2 to 8 seconds, but if the load is increased, the absolute dispersion decreases to less than 1 second and the relative dispersion decreases likewise. Thus the time interval at the end of which the seizure appears can be accurately determined for very heavy loads. The load is plotted as abscissa, the time to seizure as ordinate (fig. 35). With fatty oil and for a load below 50 kilograms, there is no seizure; for the same load, pure mineral oil permits seizure after an interval of from 4 to 5 seconds. For a load of from 50 to 100 kilograms per millimeter², sulfurized mineral oil does not prevent seizure while fatty oil permits seizure after about 8 to 10 seconds. For loads of more than 150 kilograms per millimeter², sulfurized oil gives seizure after a time interval four times longer than that for corrosive oil containing phosphorus trichloride PCl_3 .

(3) Applications:

The applications fall in two categories depending upon whether the combination opposing seizure is formed in a previous operation or results from contact with the lubricant.

An example of previous formation is found in the copper coating of steel wire to be wiredrawn or the electroplating of gears with copper. Copper, a good heat conductor, with low elastic modulus, lowers the contact temperature and does not give filiation with the iron. Another example is the phosphate treatment of rods intended for drawing by dipping in a solution of monobasic manganese phosphate; there are formed unstable monoacid phosphates which are divided into soluble monobasic phosphates which reconstitute the attacking liquid and neutral phosphates which form a continuous, adhesive, microcrystalline and porous surface layer. The latter retains the oil during the drawing process and opposes direct contact between metal surfaces.

Among the liquids forming a protective layer even during lubrication, there are the soluble sulfurized oils used for cutting of steel, the corrosive oils with S_2Cl_2 or PCl_3 used for rear axles of modern automobiles whose couple (gears) with hypoid shape necessitate both high pressure and high rates of sliding.

While in the latter case, one modern practice consists in forming the iron phosphide in a preliminary chemical operation, such a process is not suitable for cutting since the surface to be treated with sulfur is the surface in contact with the tool which is renewed continuously during the machining. The preliminary formation is possible in the case of gears because it results, in the initial period of operation, in avoidance of seizure which results from excessive local pressures. Once the period of adaptation, call for short, running-in period, has passed, there is no more abnormal pressure and if the protective layer has disappeared due to wear, no damage results.

26. Synoptic Table

The different cases of lubricated friction obtainable under various pressures are presented in table 12:

TABLE XII.- SYNOPSIS TABLE OF LUBRICATED FRICTION

Type of friction	Lubricant	Pressure kg/mm ²	Speed	F [friction coef]	Thickness of layer introduced	Remarks
Complete lubrication, hydrodynamic flow, viscous friction	Mineral oil	Very low $\frac{1}{100} < P < \frac{1}{2}$	High	0.05 to 0.002	1,500 Å	No contact nor wear in steady state, wear at start due to local seizing
Boundary lubrication stratified layers	Mineral oil	$\frac{1}{100} < P < \frac{1}{2}$	Low	0.05 to 0.01	250 to 1,500 Å	Marcellin strato-film, no wear
Incomplete lubrication, greasy, by mono-molecular films two layers minimum	Oils containing traces of fatty acid	$10 < P < 50$ or 80	Low	0.08 to 0.03	46 Å	Wear by tearing-out break of metallic soap and acid corrosion
Lubrication for extreme pressure	Sulfurized oils	$50 < P < 100$	High	0.25 to 0.10	Thickness of two layers of formed metallic sulphide Interference colors	Direct contact between bodies
	Soluble sulfurized oils					
	Water + colloidal S					
	Corrosive oils S_2Cl_2	$100 < P < 150$	High			Wear by tearing-out of sulphide and sulphuration
	Corrosive oils PCl_3	$150 < P < 200$	High			

27. Abrasion Due to Dust

If the material of one of the two rubbing surfaces is soft, we find abrasive material embedded in the soft material and scratches on the harder material; it is a general practice to give both materials the same surface hardness if scratches are to be avoided. Obviously, if we succeed in giving both surfaces a greater hardness than the abrasive dust particles, the latter are ground very fine. Also, for rubbing surfaces, use is made of extra hard tempered steels, to hardened carburized steels, to semihard steel hardened superficially either by blowpipe (flame) or by high frequency induction heating, to cyanided and tempered steels, to special steels cyanided at low temperature or to mitriding. Use is made also of white cast iron, chill-cast iron, or of chrome, molybdenum or tungsten cast iron. For extreme hardness, sintered tungsten carbide is available.

Bearing metals, composed of hard grains in a soft matrix, have relatively good resistance to abrasion. In fact, the dust is embedded in the two metal surfaces in such a way that

$$F = s\Delta = S\delta$$

if S is the area of the impression in the soft metal of hardness δ and s the area of the impression in the hard steel of hardness Δ .

The deep embedding of dust in the soft metal therefore prevents deep scratches in the hard metal. Contrary to the preceding rule, a great difference in hardness is desirable in this case (figs. 36 and 37).

In the case of lead bronze composed of a copper matrix with lead globules, the hardness of the matrix is 50 Brinell. It is generally used in combination with steel, surface hardened to give a hardness of 600 Brinell; we see by the following relationship:

$$\frac{\delta_{Cu}}{\Delta \text{ hard steel}} = \frac{50}{600} > \frac{\delta_{Sn}}{\Delta \text{ ordinary steel}} = \frac{8}{300}$$

It is readily seen that scratches are more apt to occur on a crankshaft in the presence of lead bronze even when these crankshafts are surface hardened than on a crankshaft of ordinary steel in the presence of babbit bearings.

28. Corrosion Friction

Corrosion friction, which has received very little study, manifests itself when the two surfaces in contact are immersed in an electrolytic solution and especially when the solution is corrosive.

The contact of the two metals produces an electrochemical couple which initiates either anodic attack (and with it, corrosion) or anodic passivation, (and in this case the film may have a protective role by preventing chemical attack and seizure by filiation between the metallic surfaces); abrasion can, however, still occur in the protective layer and, if this layer is harder than the underlying metal, wear decreases. If this anodic layer is softer than the underlying metal, wear increases.

In general, under conditions of friction in the presence of an electrolyte, some benefit accrues from good dissipation of the heat which make it possible to use materials that are less heat-conducting than the metals and that are resistant to seizure and to corrosion effects - bakelite reinforced with cloth and pressed in a mold or else a blend of bakelite and graphite molded in a press or pure graphite machined in the mass. These processes give excellent results and are used in the chemical industry; the use, for rolling mill housings, of bearings with bakelite base wetted by water should also be noted.

CHAPTER 5

DRY FRICTION

Friction in dry air is accompanied by a substantial rise in temperature, oxidation, seizure, and tearing-out of material. The result is that these tests are very badly defined (irreproducible) and that it serves no useful purpose to specify the state of the surface, the latter being changed from the first minutes of the test. Be that as it may, that which follows refers to surfaces with an initially ground state.

Specific wear:

The loss of weight per unit surface as a function of the distance traversed in sliding shows a proportionality; therefore, all subsequent diagrams show the variable as abscissa and, as ordinate, the specific wear as weight loss per unit surface per unit of distance traversed.

29. Steels

This chapter on dry friction is based on the tests by R. Mailander and his collaborators, Raedeker and Dies, and summarized by Descroix. Only the laws involved in these tests are discussed, the experimental part will not be discussed.

(1) Existence of two normal zones and a transition zone:

The tests were not very accurate, as said before, and present, therefore, a certain scattering which make their representation by a curve impossible. The representative points are included in a zone characterizing the scattering of the results. Figure 39 shows first an increase in the specific wear, then a disturbed transition zone, and finally, a second zone where the specific wear again increases with the load.

On extrapolating, it is seen that, for an identical load, the specific wear in the second zone is less than that of the first.

The first zone is characterized by the formation of powdery ferric oxide, little adherent to the polished surface. For ordinary steel with a hardness of 130 at the core, the hardness at the surface increases to 380 by work hardening; there is no seizure because there is no possibility of filiation between the rubbing surfaces as a result of the interposed oxide.

In the disturbed intermediary zone, metal is torn out by seizure, the sheared surface is white, shiny, and has a Vickers hardness of 750 which is about equivalent to a sudden quenching.

In the second zone, the layers of the steel are heated considerably which results in smearing or high temperature deformation. In consequence of the annealing due to this heating, the increased hardness does not exceed 280 Brinell, the metal is less work hardened than in the first zone. The projections which accompany the seizure burn leaving black and bluish gray scales. These projections are similar to those obtained in grinding.

Considering the variations of the couple as function of time (fig. 40), it is found that in the first zone the friction couple remains low and the oscillations small, while in the second zone the coefficient of friction is much higher and the oscillations greater. There is much seizure in the second zone.

(2) Metallographic changes:

These changes are twofold, structural and chemical. From the structural point of view, it is convenient to represent the alteration of the metallic layers by the hardness (fig. 41). Considering this hardness as a function of the load, for a core hardness of 130 for example, the surface is work hardened to about 380 in the first zone and then decreases to about 280 on reaching the second zone, characterized by hot smear. It is found further that (fig. 42) the work hardened depth and thickness of the white martensitic spots increase with the load.

(3) Oxidation:

The oxide or the oxidized projections can be analyzed by defining the nature and the amount of formed oxides.

It is found (fig. 43) that, at the lowest conditions of operation of the first zone, the oxide Fe_3O_4 is formed, with a small amount of FeO . As the conditions become more severe, the amount of Fe_3O_4 becomes less and that of FeO more; free metallic iron is also formed in the oxide powder.

At the beginning of the transition period, the amount of free iron and of FeO passes through a maximum while the amount of Fe_3O_4 passes through a minimum. The proportion of Fe_3O_4 in the transition period increases therefore at the expense of FeO and Fe .

From the start of the second zone, Fe_2O_3 oxide appears in the projections, the proportion of which increases as the operating conditions become more severe. The projections have the concretionary structure of the oxide of iron scales, a small nucleus of iron surrounded by concentric layers of FeO , Fe_3O_4 , Fe_2O_3 extending from the core to the periphery.

The oxidation phenomena are the logical consequence of the temperature rise with the increasingly severe operating conditions. This is readily apparent from the equilibrium curves of iron and its varieties of oxide established by Chaudron (fig. 44) in the presence of CO and CO_2 , because if the iron is oxidized, the carbon of the steel must also burn producing CO and CO_2 .

Below 580°C , Fe_3O_4 is the only stable oxide in contact with the iron; hence, it is the one that must be formed at the lower zones. At temperature above 580° , it is the FeO oxide that is in equilibrium with the iron, hence which predominates in the most severe conditions of the first zone.

In the second zone, the projections are subjected to a brisk combustion with sparks; the metal and the carbon are oxidized and burn in air. The entire gamut of oxides is covered, up to the final product Fe_2O_3 .

(4) Relationship between the two zones of wear and the transition point of steel:

Consider the increasingly severe conditions of friction obtained by increasing either the pressure or the speed. The heat freed at the surface of contact increases and with it the temperature of the adjacent areas. This temperature rise acts on the metallographic structure in the test specimen and on the oxidation reactions at its surface.

The metallographic structure of the steel passes from the ferrite plus cementite aggregate to the austenite, but at the transformation temperature of the steel since the superficial deformations of the test specimen stem from the dependence of contiguous subjacent layers, the metallographic transformations of these layers also affect the friction. It is not sufficient that, to pass from the first to the second zone, the area of contact pass to the γ state; this transformation must also hold for the subjacent layers, which necessitates much more severe conditions of friction. The transition between the first and second zone is therefore extended over a wide range of pressure in a test at constant speed.

In the low zone, the wear occurs to the alpha state with a severe work hardening; in the high zone, the steel attains the gamma state with plastic deformation without cold hardening. The transition zone is characterized by the fact that the hardening temperature is reached at certain points of the surface but the mass temperature remains low enough to enable constituents of hardening to be obtained by quick cooling (quenching) on leaving the contact zone.

The dry wear tests indicate that the appearance of the transition zone is not characterized by any discontinuity in the nature of the oxides. What is more, toward the end of the transition zone, the oxide is 80 percent Fe_3O_4 as at the beginning of the first zone under the mildest conditions. The oxide can therefore not be held responsible for the change which is dependent solely on the ferrite + cementite \rightarrow austenite transformation.

Another proof, as will be shown later, is found in the fact that the wear curves in an atmosphere of nitrogen or hydrogen have the same variations as in air and likewise exhibit two distinct zones.

(5) Effect of speed:

The curve of the specific wear can be plotted against the load at constant speed. The speeds increase from one test to the next.

It is found (fig. 45) that the specific wear for each one of the two zones increases with speed and that the change from the first to the second zone is effected at loads which are lower as the speed is higher. This is quite sensible and explains the double overlap of the wear curves.

(6) Effect of humidity:

On plotting the specific wear against the load (fig. 46) for different humidities, it is found that in the first zone the oxidation and the loss of weight increase with the concentration of water vapor; in the second zone, that the water vapor has the effect of making the oxide more adherent, filiation less easy, and loss by projection lesser, hence favorable action on the wear resistance. The cooling action of the water on passing from the first to the second zone requires so much greater pressure as the water content is higher.

(7) Effect of the nature of gas:

The atmosphere acts largely through its hot chemical reactions on the steel and to a lesser degree through its heat conductivity. The experiments indicate (fig. 47) that hydrogen and nitrogen, which in the experimental conditions produce no binary compounds superficially by chemical reaction with the iron, cannot oppose the seizure produced from

the first zone; hence the specific wear curves plotted against increasing load are higher than in the presence of air. The heat itself is higher and the second zone appears sooner (at lower load) also as a result.

In the case of nitrogen (fig. 48), a little nitride is formed but not enough to prevent seizure. The concentration of nitrogen in the dust particles decreases with increasing temperature in both the first and the second zone.

There are two cases, however, where the specific wear curve presents no discontinuity and corresponds to the second zone even for the smallest loads, that is, where the local heating becomes appreciable whether as a result of reduced cooling as in the vacuum test or of brisk combustion to Fe_2O_3 as in pure oxygen. (Curves E and C, fig. 47).

(8) Effect of the micrographic structure:

The study of the effect of the micrographic structure has sense only to the extent that the local heating due to friction does not promote its destruction. A suitable method of analysis is to take the maximum specific wear, or characteristic wear, at the end of the first zone as criterion of comparison and to record its variation with respect to the carbon content and the conditions of treatment which determine hardness and micrographic structure.

Consider the heat treatments including a heating above the transformation point and a range of cooling rates (fig. 49). The characteristic wear for one steel, hence for one carbon content, will be so much less as the rate of cooling is greater. The characteristic wear for an identical rate of cooling is so much less as the carbon content of the steel is greater.

As to the treatments obtained by following the brisk hardening by tempering over a range of temperatures, (fig. 50), the characteristic wear on one steel will be so much greater as the tempering process was intensified. For the same tempering temperature, the more the steel is carbonized, the smaller the characteristic wear. This proves that the wear resistance varies, other things being equal, as a function of hardness; therefore, the characteristic wear can be plotted against hardness. Every degree of hardness can be obtained by varying composition and heat treatment. According to figure 51, the results of the characteristic hardness are widely scattered for low hardness but grouped rather well for very great hardness, without direct relation to carbon content.

On separating the hardness obtained by tempering at controlled speed from that obtained by tempering at suitable temperature (fig. 52), it is readily seen that the structures obtained by controlled cooling results in a much less characteristic wear than those obtained by tempering controlled for an identical hardness.

These results show the influence of micrographic structure. The distinction between these micrographic structures is shown in figure 53.

As regards the stable structures, lamellar pearlite (1) (fig. 53) gives a much lower characteristic wear than coalesced or globular pearlite (2) of the same hardness; also, fine lamellar pearlites (1) offer more resistance (to wear) than the finest granular structures (3). Lastly, the bainite structures which constitute the less hard region of the branch of curve (4) present a characteristic wear as pronounced as the finest lamellar pearlites although having a substantially higher degree of hardness. We must obviously obtain either the hardest martensites, most difficult to temper, or structures lightly hypertempered (martensite with a little residual austenite) for which, as a result of the stability at reheating, the characteristic wear falls a little below that of the lamellar pearlite.

To combine machinability and lack of brittleness (ductility) with adequate resistance to dry wear, it is recommended to resort to the finest lamellar pearlites, as is the case of brake drums and, to some extent, engine cylinders because the lubrication of the latter may be uncertain. If, on the other hand, it is desirable to take advantage of tempering structure, the martensite must be stabilized by special elements such as chromium, which retards the temper and to employ a lubrication which, if it should be uncertain, reduces the heating as indicated by Hughes. Also, ball bearings are of extra-hard, chrome, tempered steel and are lubricated.

30. Dry Friction of Other Alloys

(1) Alloys rich in Cr, Si, Al:

In the dry friction of steel with 13 percent chromium, the oxide layer formed hot is adherent so that the resulting friction is not accompanied by seizure and the specific wear is slight. Furthermore, the wear is so much less as the alloy itself is harder and retains its hot-hardness; also, the martensitic structure rich in chromium and the presence of hard carbides is itself favorable. It is for this reason that the mild steels with 2 percent carbon and 13 percent chromium are used satisfactorily for dry friction pieces.

In the case of Ni-Si bronze, and especially aluminum bronze, the layers of Si and especially of Al oppose seizure over a wide range of pressures and speeds.

(2) Gray cast iron:

The dry friction tests on the Amsler machine with a steel roller rubbing against a gray cast iron roller showed a low and regular

coefficient of friction under the conditions of pressure and speed which, when the two rollers were of steel, would show the high and irregular friction, characteristic of incipient seizure. The steel roller is covered with a thin film of graphite at the expense of the cast iron. The graphite, rolled in between the two rollers, is opposed to filiation and, owing to its laminated structure, assures a low coefficient of friction.

If the test is continued for a long period, the graphite is slowly and progressively used up and leaves as dust until all the graphite is finally gone from the surface of the cast iron roller. At this moment the coefficient of friction increases and becomes unstable, there is seizure, and the surface of the cast iron roller, devoid of graphite, is changed rather quickly by tearing-out. Thus, the cast iron has self-lubricating properties in dry friction but they do not last indefinitely.

If it is lubricated, the graphite acts moreover by forming oil pockets which permit a perfect hydrodynamic flow. For this purpose, graphite solidified in finely and evenly distributed lamellae is much more efficient than nodular graphite of annealing.

The nature of the matrix has also great significance as regards wear. Piwowarski and Heimes have shown (fig. 54) that the wear of pearlitic cast iron is from 6 to 10 times less than that of ferritic cast iron with the same graphite distribution.

Furthermore, very recent studies have shown that the martensitic material which can be obtained by the hardening of a pearlitic cast iron permits, for equal distribution of graphite, a reduction in wear to a third. This gives the best research results for engine cylinders. The different qualities demanded for castability of cylinder blocks and the friction of the inner surface of cylinders may result in the use of different cast irons, hence of the liners. A recent technique consists in superficially heating the inside of the liners by electromagnetic induction before quenching with water to assure a superficial martensitic structure without deformation of the piece or change in the solidified graphite structure.

(3) Copper-lead and iron-lead alloys:

Dry, the lead is rolled on the surface of the cuprous alloy and ends by coating the whole rubbing surface which, initially of a rose color, becomes metallic white and glazed. Since the lead produces no filiation with either iron or copper, this insertion of lead is opposed to seizure. The coefficient of friction remains low and steady owing to the softness of the lead which is rolled between the rubbing surfaces.

The same property is utilized in the cutting steels containing lead. The fine, evenly distributed inclusions of metallic lead prevent the chips from sticking to the cutting tool.

CONCLUSION

The survey of the mechanisms accompanying friction has shown their complicated nature which, at every instant, involves the fine geometric configuration of the separated surfaces as well as the physical, chemical, and mechanical properties of the transient layers which can exist in solids as in the ambient fluid near these contact surfaces. This complexity is increased by the changing character of the friction phenomenon and the continuous changing of the surfaces due to wear.

Another character of friction is the high local pressure and temperature with its accompanying variation of the scale of the observed phenomena.

Lastly, there is a whole series of transitions under conditions initially as well defined as boundary lubrication, greasy friction, and dry friction. The wear appears not only as tearing-out of metallic particles or mechanical abrasion but more often as tearing-out of the thin film resulting from the chemical reactions between the metal and the surrounding medium or chemical erosion.

From the practical point of view, this analysis shows that each problem of friction or wear requires its particular solution. There is no universal solution; one or the other of the factors predominates and defines the choice of the solution. In certain cases, copper alloys of great thermal conductivity are preferred; in others, plastics abundantly supplied with water. Sometimes, soft antifriction metals are desirable to distribute the load; at other times, hard metals with high resistance to abrasion or heat. In all these cases, one will try to avoid mechanical filiations by the choice of the metals in contact.

As regards the lubricants, an entire scale of properties can be obtained with the lubricating oils by controlling their viscosity and on the oiliness since these two properties are independent and by no means incompatible, but this field can be enlarged by graphite and colloidal lead as well as by aqueous lubricants which have their chosen domain. The surface treatments by sulphurizing, phosphiding, phosphating, electrolytic deposition of lead, cadmium, copper, and brass have their preference, each in its well-defined field.

It is for the skill of the engineer to define each friction problem and find the most adequate solution for it. We shall have attained our aim if this article contributes in a slight measure toward a better

classification and identification of the innumerable cases in industrial practice.

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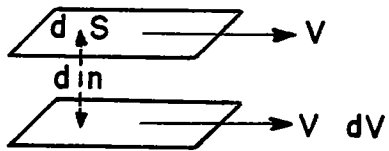


Figure 1.- Viscous friction of liquids.

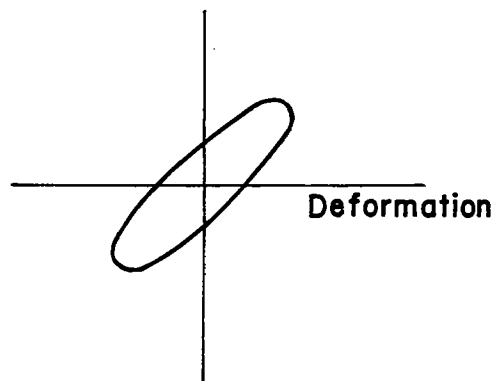


Figure 2.- Internal friction of solid bodies.

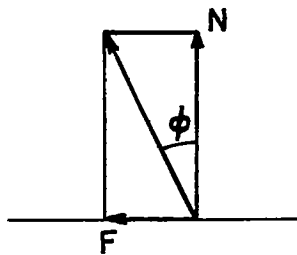


Figure 3.- Sliding friction.

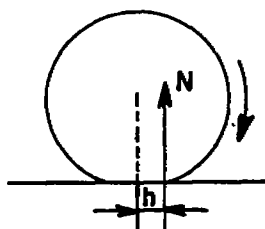


Figure 4.- Rolling friction.

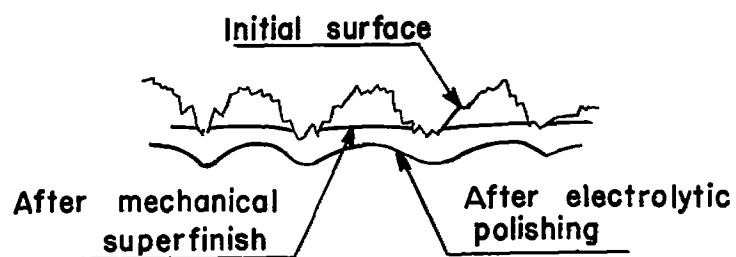


Figure 5.

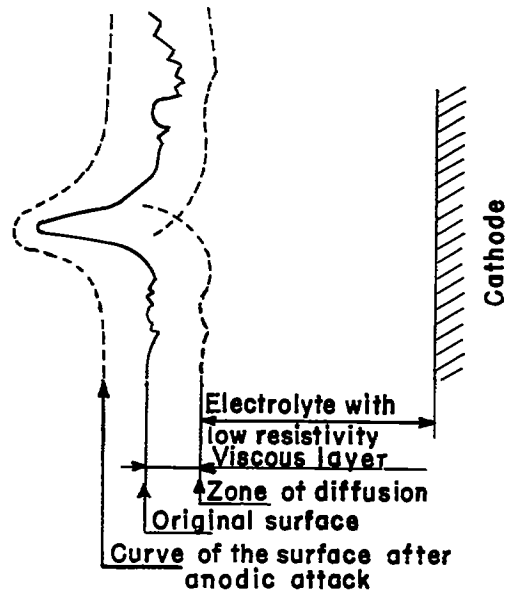


Figure 6.

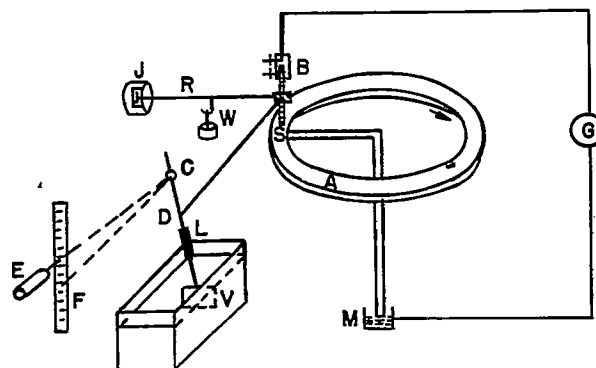
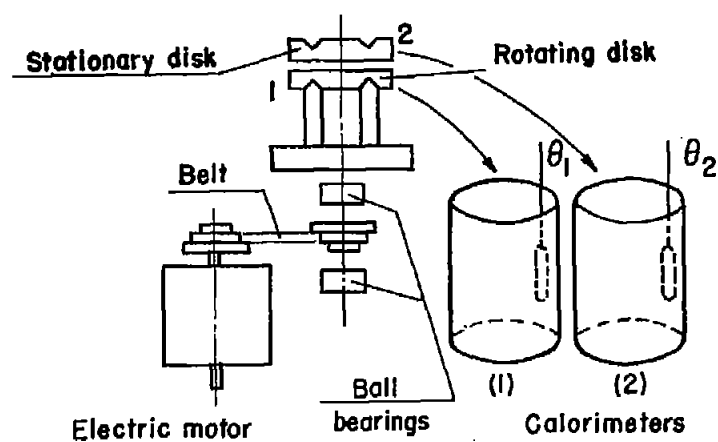


Figure 7.- Hughes' experiments (1937, Cambridge) contact temperature.



Charron's experiments, 1939 (Study by Vernet, 1938)

Figure 8.- Heat distribution between two solid bodies.

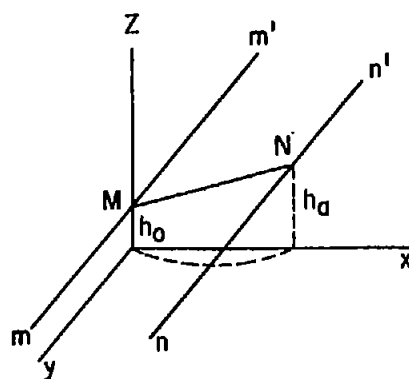


Figure 9.

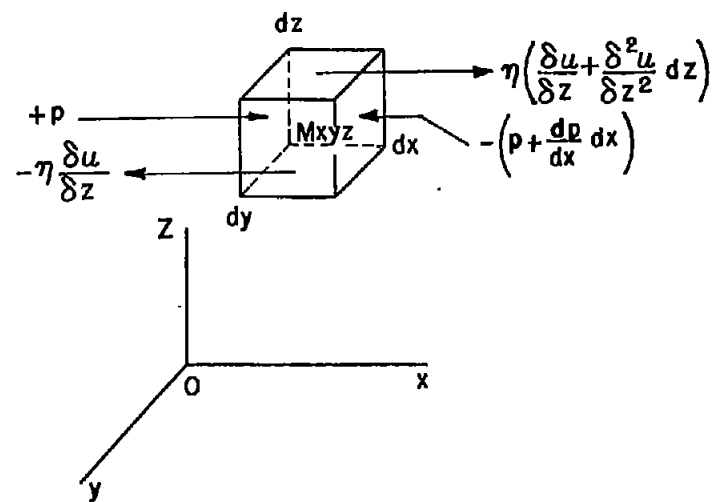


Figure 9a.

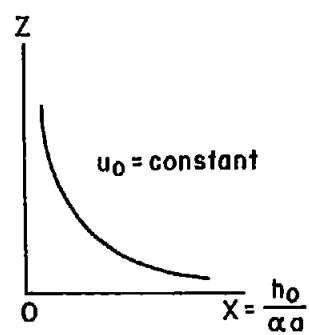


Figure 10.

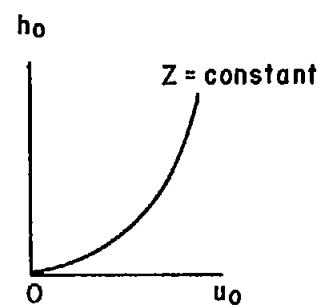


Figure 11.

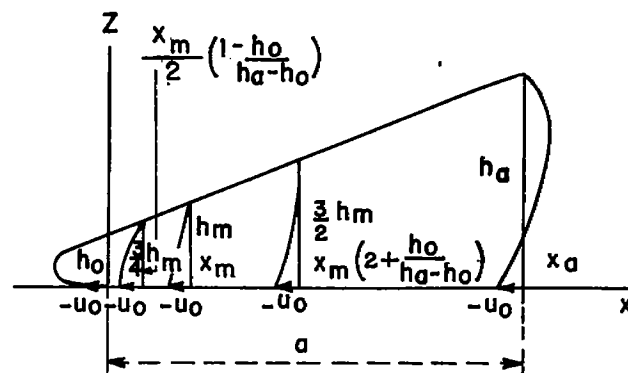


Figure 12.

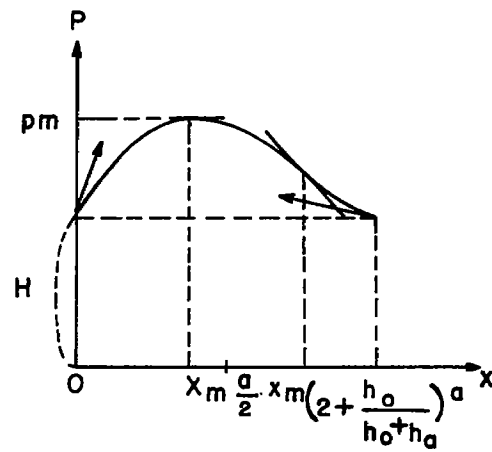


Figure 12a.

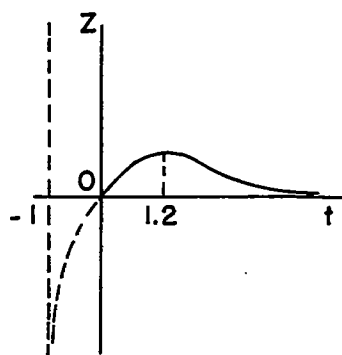


Figure 13.



Figure 14.

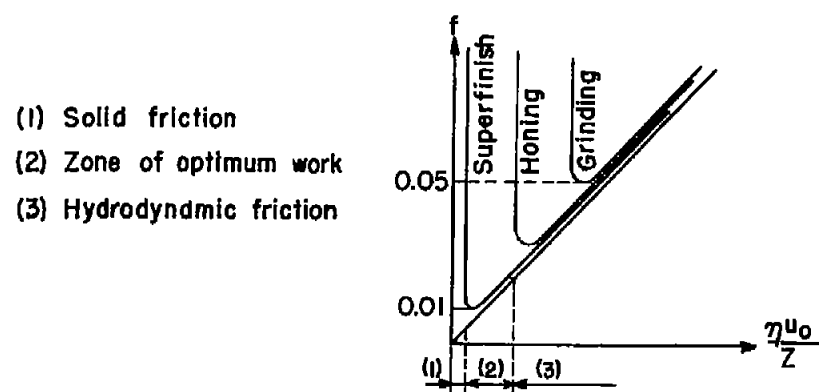


Figure 15.- A. M. Swigert.

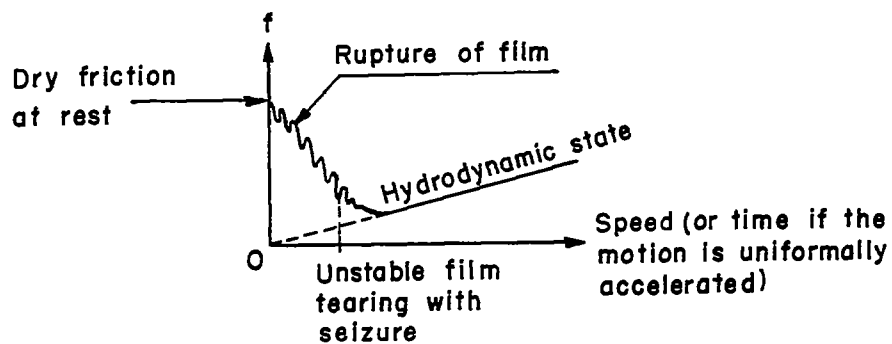


Figure 16.- Establishment of the hydrodynamic state starting from rest.

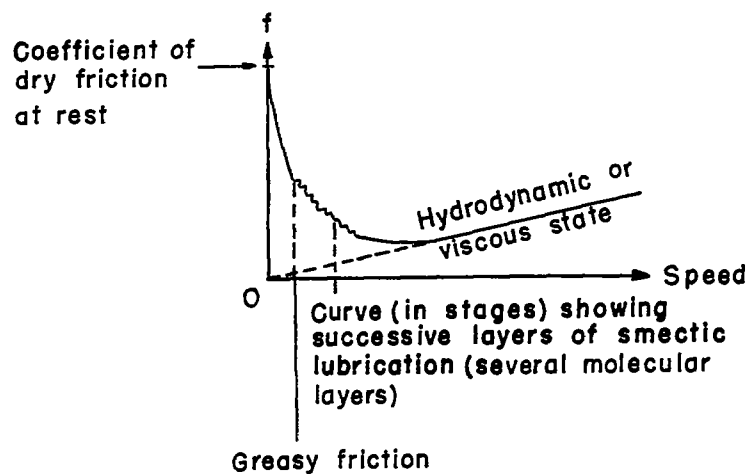


Figure 17.- Establishment of the hydrodynamic state starting from rest.

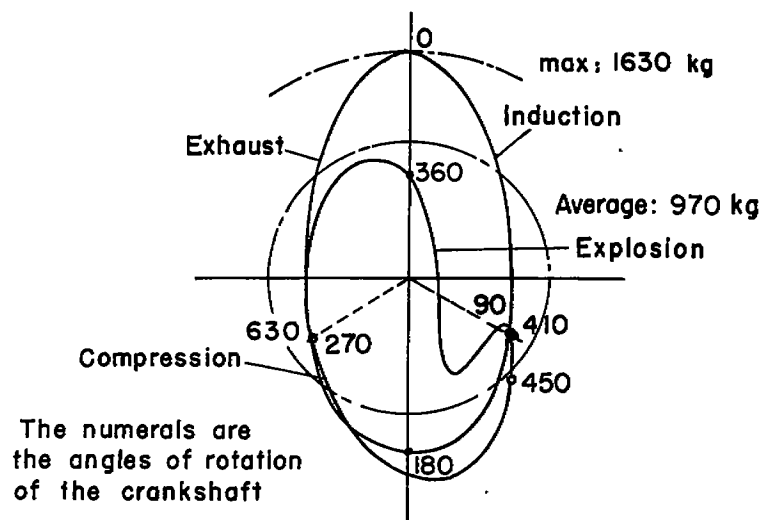


Figure 18.- Internal combustion engine. Connecting rod - crank mechanism.

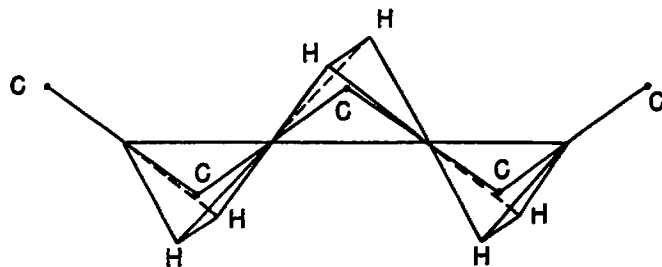
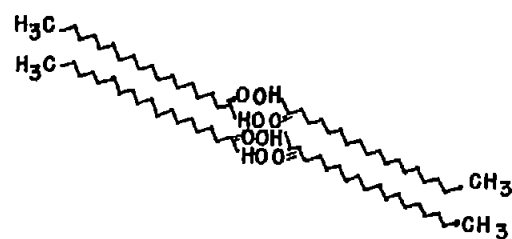


Figure 19.- Saturated hydrocarbon chain.



4 molecules per mesh
monoclinic network

$a = 5.546 \text{ \AA}$ $b = 7.381 \text{ \AA}$ $c = 48.84 \text{ \AA}$

Figure 20.- Schematic of crystalline stearic acid.

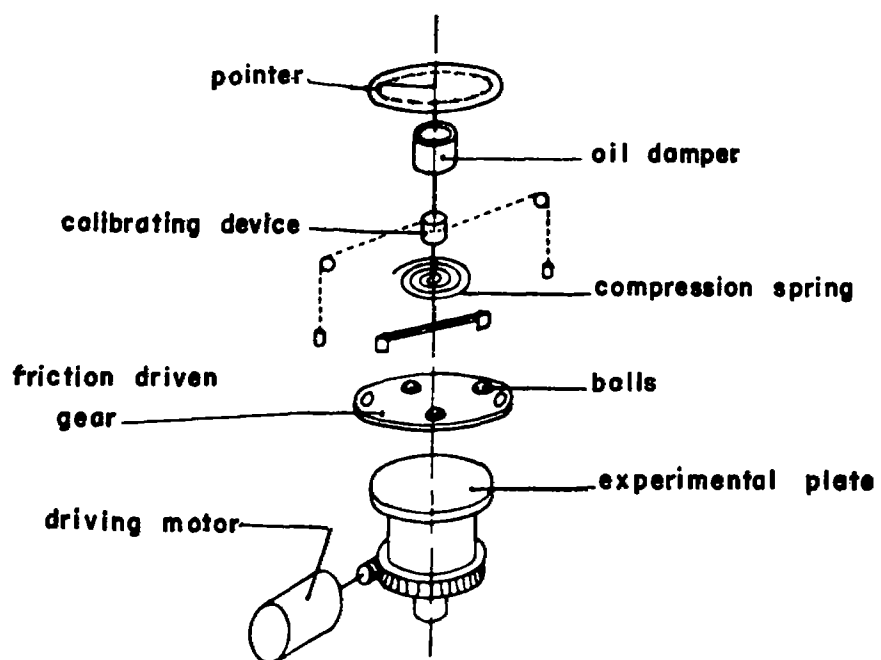


Figure 21.- Herschell apparatus.

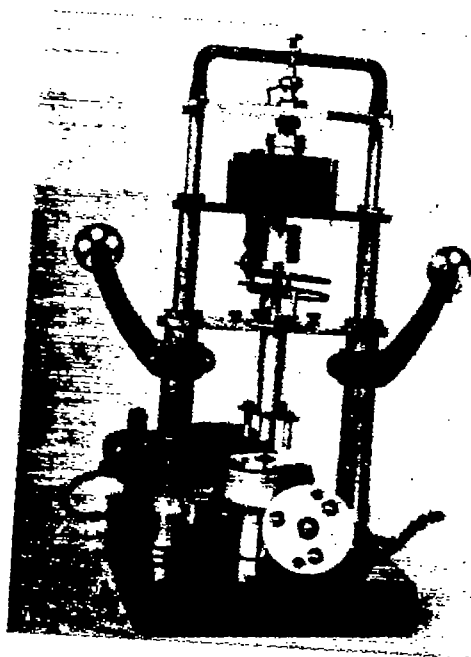


Figure 22.- Herschell apparatus.

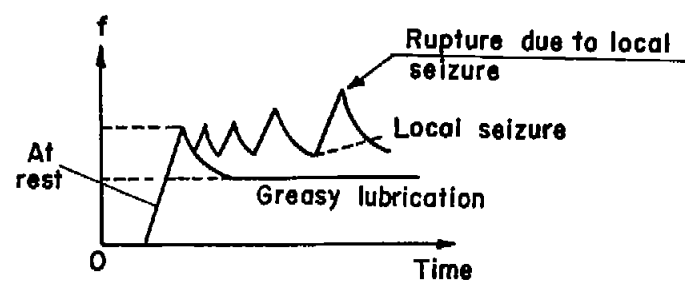


Figure 23.- Aspect of curves - friction time according to the Herschell apparatus.

Ball: steel 1.2 C and 1.4 Cr hardened
Plate: pure silver
Temperature: 20° C

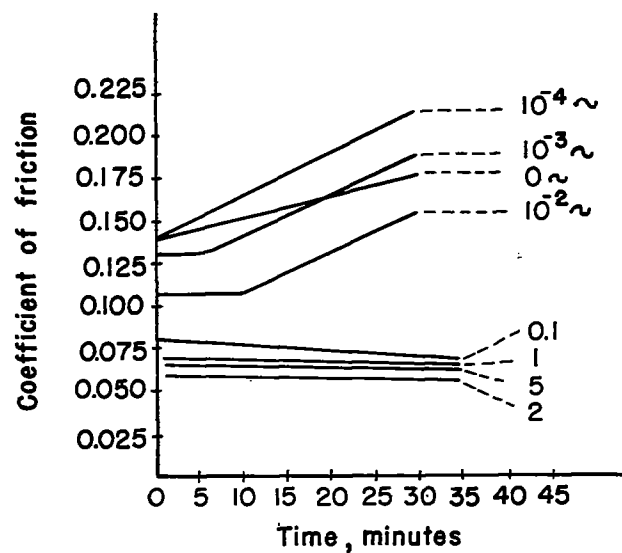
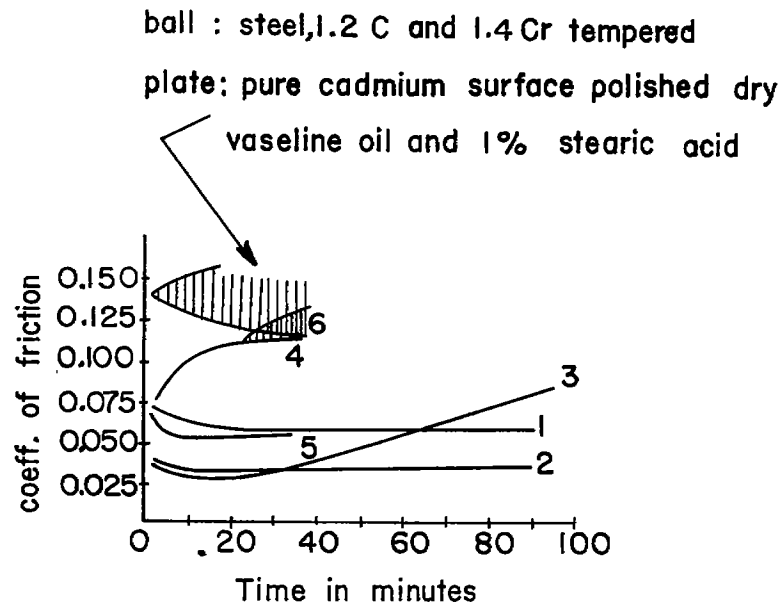


Figure 24.- Effect of stearic acid concentration in percent in vaseline oil.

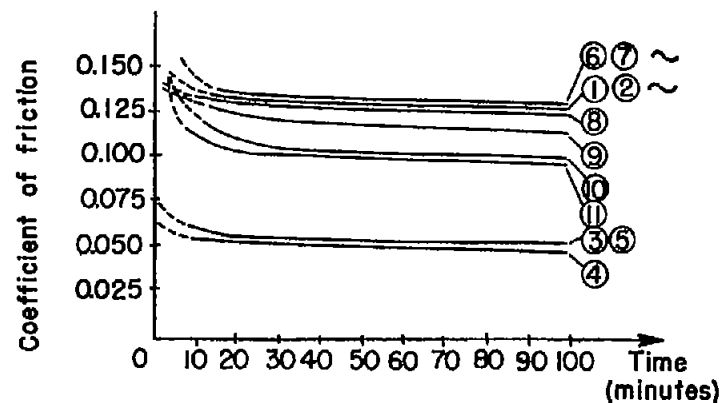


1. Test at 30° 2. Test at 70° 3. Test at 100°
4. After test 100°, #3, new test at 30°
5. Plate washed - new oil
6. Plate repolished - used oil

Conclusion :

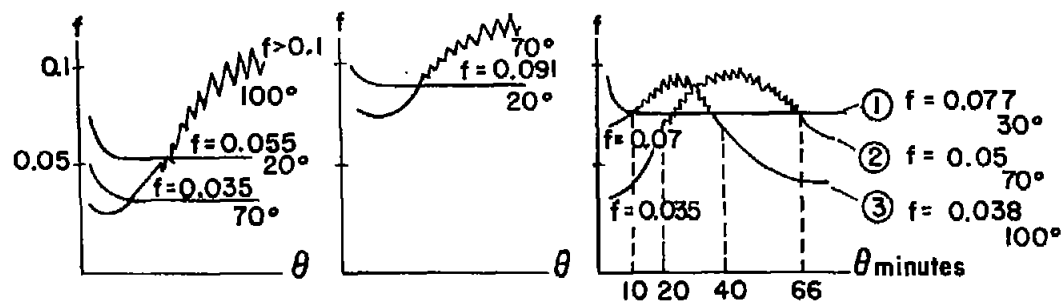
4. The oilness does not appear reversible
5. The plate is not appreciably altered
6. The oil has lost its properties

Figure 25.- Corrosion changes in greasy lubrication.



Vaseline oil	Treatment			Surface
1 Alone				dry
2 Alone		4 hrs. at 120° bubbling through air		dry
3 +1% stearic acid				dry
4 +1% stearic acid				wet
5 +1% stearic acid	1 Cd	4 hrs. at 120° bubbling through air		dry
6 +1% stearic acid	shavings	4 hrs. at 120° without air		dry
7 +1% stearic acid	"	4 hrs. at 120° bubbling through air		dry
8 +1% stearic acid	"	"		wet
9 +1% stearic acid	"	"	+ 1 drop of oil *3	dry
10 +1% stearic acid	"	"	+ 6 drops of oil *3	dry
11 +1% stearic acid	"	"	2 h. boiling with water	dry

Figure 26.- Effect of change in oil; its regeneration by hydrolysis.



Lubricant. tetraline + 1%
stearic acid.

Metal ... Cadmium.

Conclusions at 100°, acid
exhausted by
corrosion.

tetraline + 1%
stearic acid,

Copper.

at 70, Cu soap
dissolved,

tetraline + 2% lead
stearate

Steel

stearate decomposed in stearine
and colloidal lead which is oily

Figure 27.- Effect of temperature and time of oiliness.

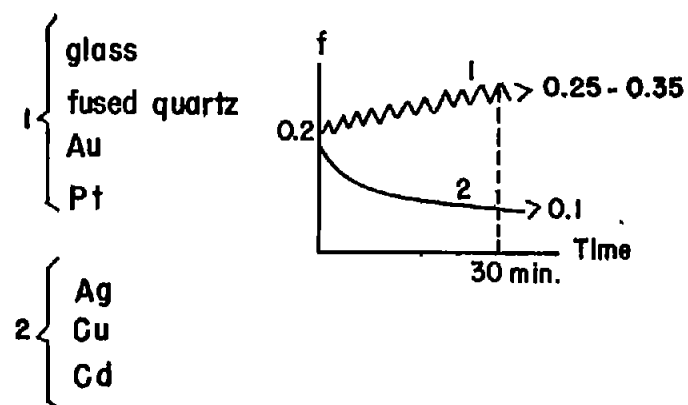
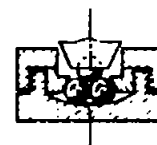
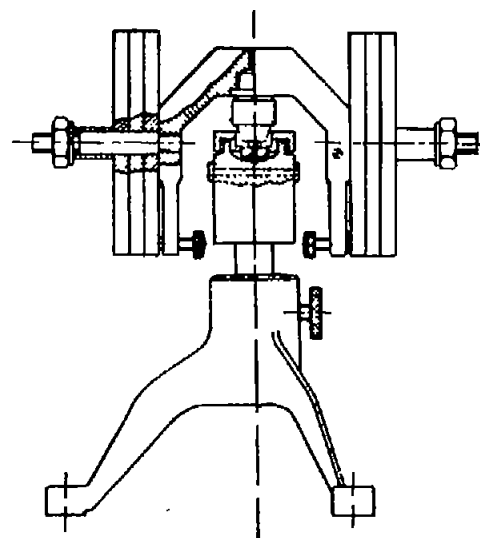


Figure 28.- Noble and reactive metals.



Pivot in detail

$$f = C \frac{n}{t^2}$$

n = number of revolutions

t = time until stoppage

C = constant depending on weight
and moment of inertia of
moving unit and diameter of balls

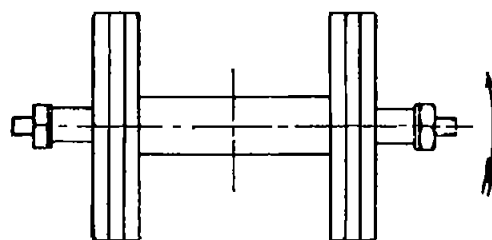
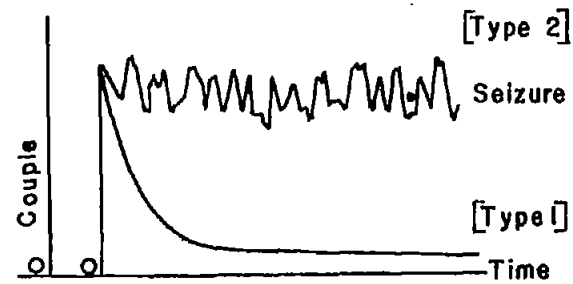


Figure 29.- Ball apparatus, studied by the Royal Dutch Shell Company,
for determining the lubricating properties of oil in boundary lubrication.



Pressure kg/mm ²	Type (1)	Type (2)
Medium < 10	Mineral oil + 1% stearic acid Mineral oil + colloidal graphite	Pure mineral oil
Heavy 10 to 80	Sulfurized mineral oil	Mineral oil + 1% stearic acid Mineral oil + colloidal graphite
Extremely heavy 80 to 160	Corrosive sulfurized oil soluble sulfurized oil wear + gum + colloidal S	Sulfurized mineral oil

Figure 30.- Extreme pressure lubrication.

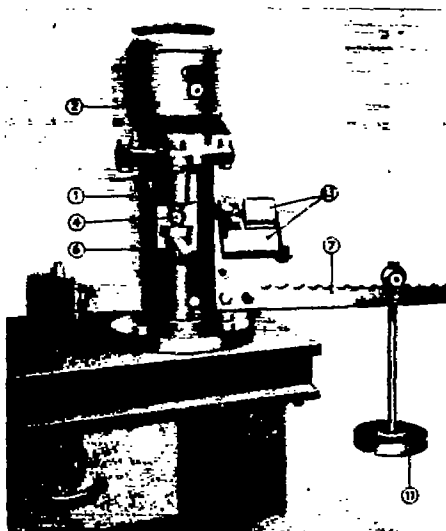


Figure 31.- Boerlage's seizure testing machine.



Figure 31a.- Boerlage's seizure testing machine.

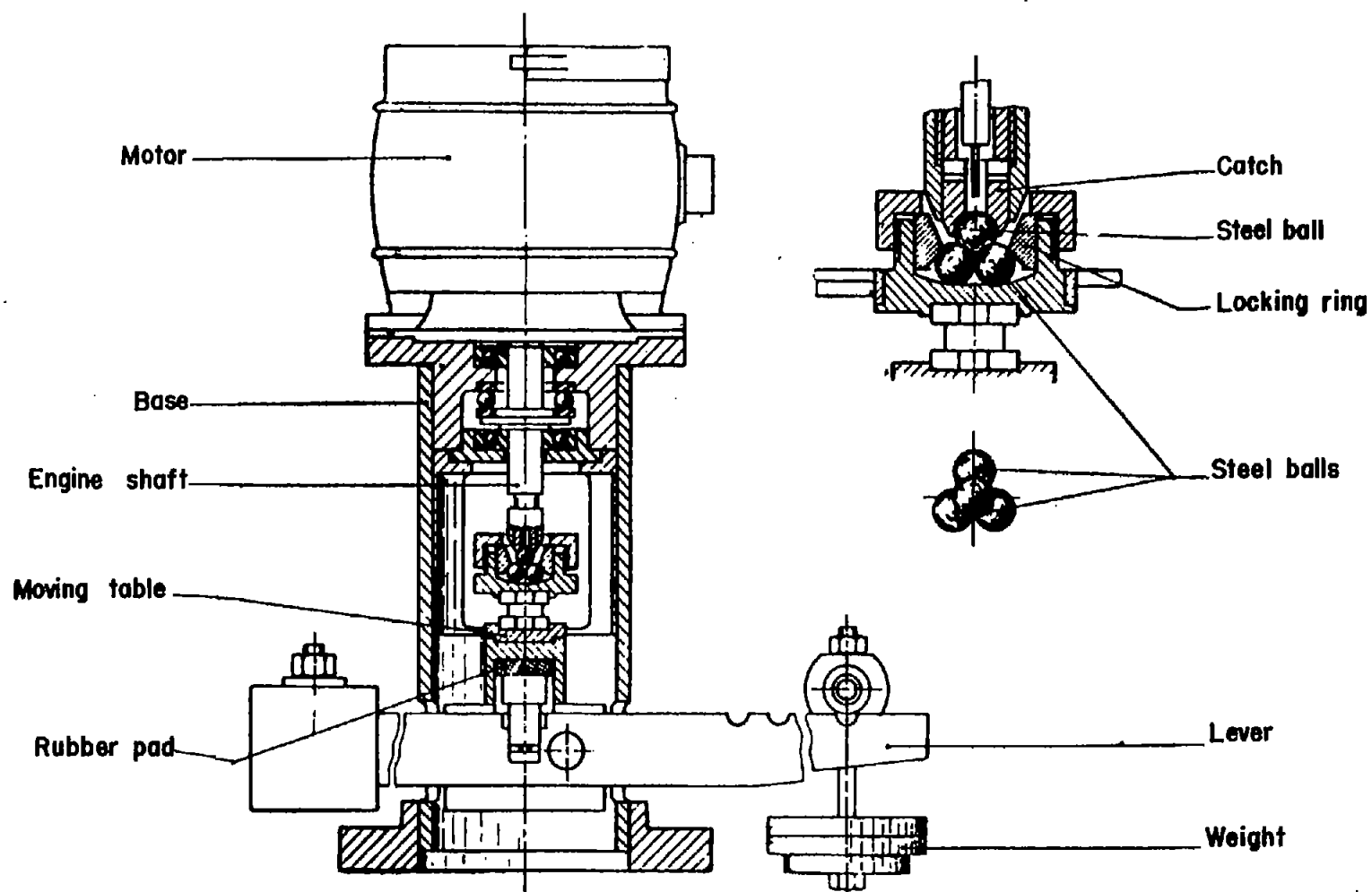


Figure 32.- Corrosive oil testing machine (Boerlage).

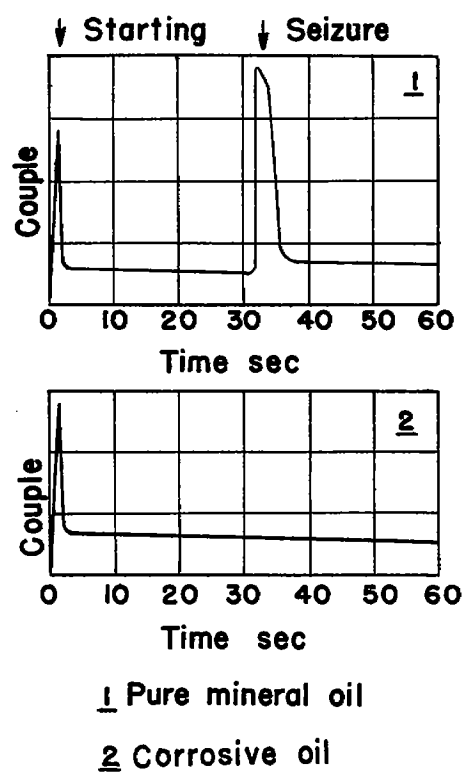


Figure 33.- Extreme pressure lubricant test with the Boerlage machine.

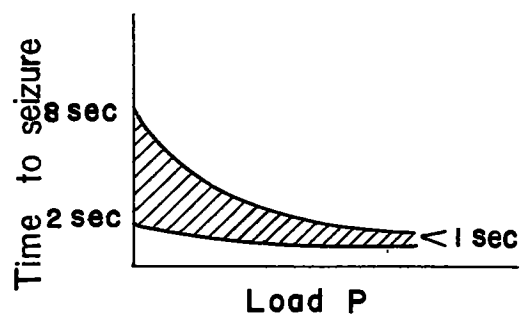


Figure 34.

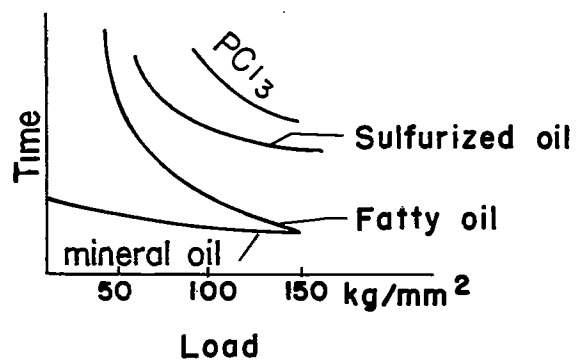


Figure 35.

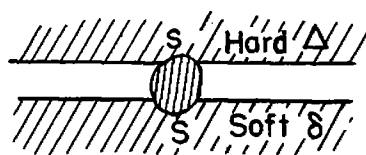


Figure 36.

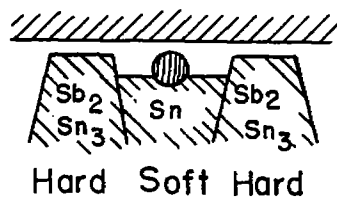


Figure 37.

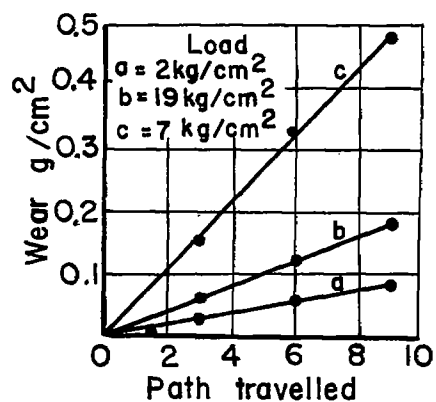


Figure 38.- Wear plotted against length of sliding path - agreement of repeated tests - Raedeker, Mailander, and Dies.

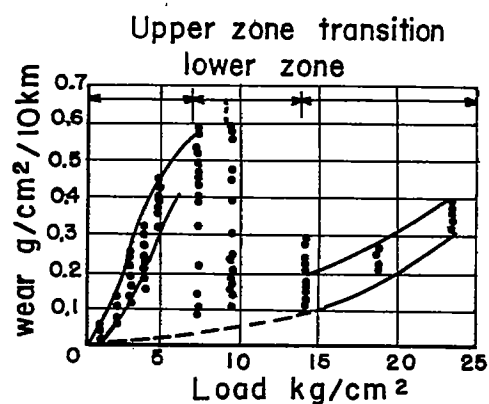


Figure 39.- Dispersion of wear confirmed by tests on various soft steel castings.

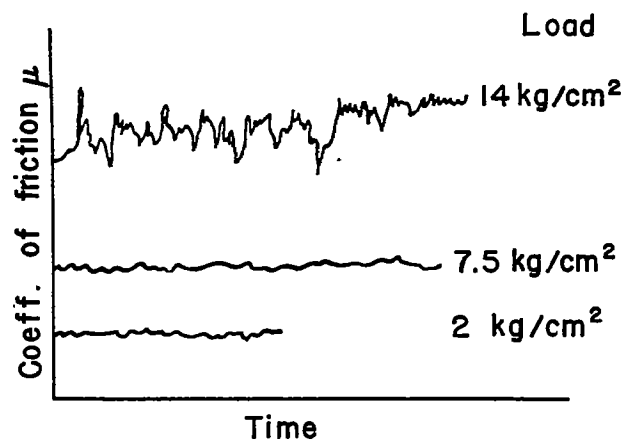


Figure 40.- Variation of friction between extra soft steel and chromium steel in air (speed = 1 m/s).

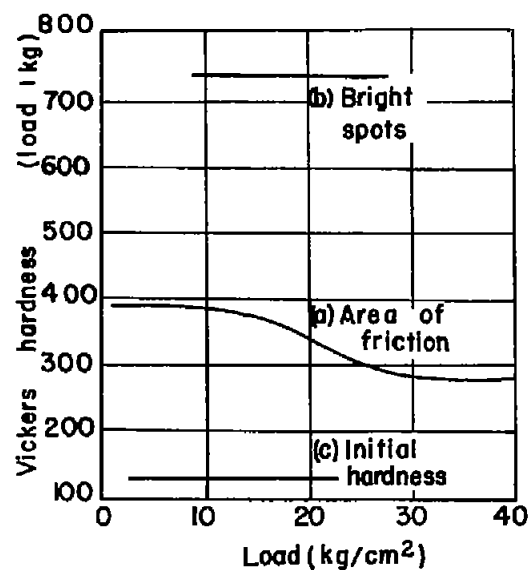


Figure 41.- Change of extra soft steel hardness in the wear surface.

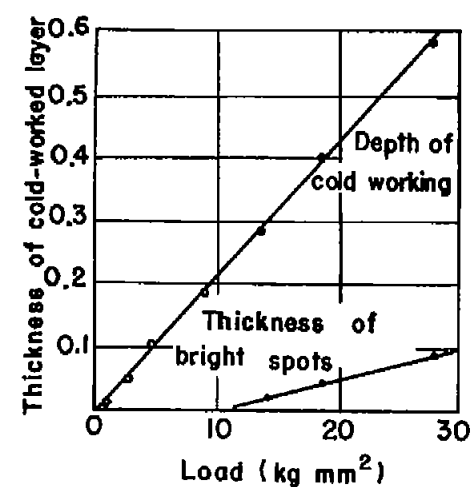


Figure 42.- Depth of cold working.

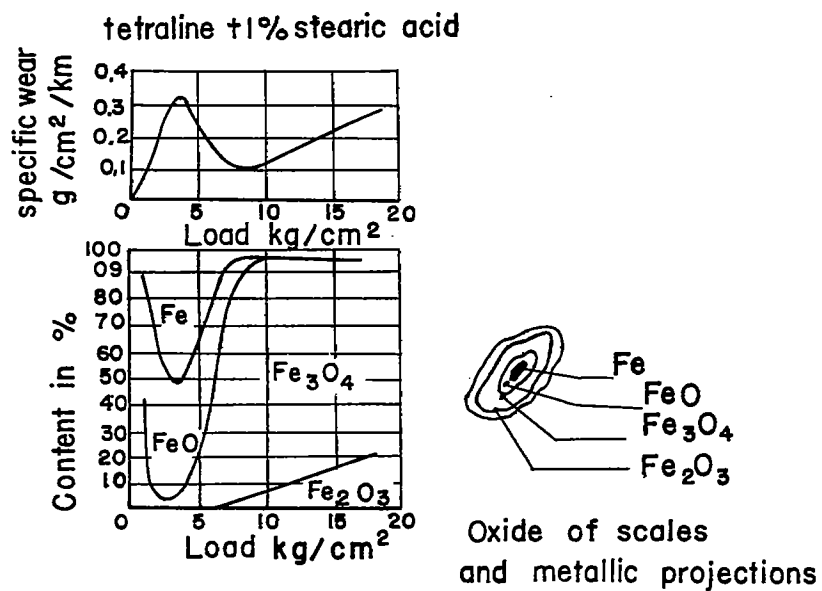
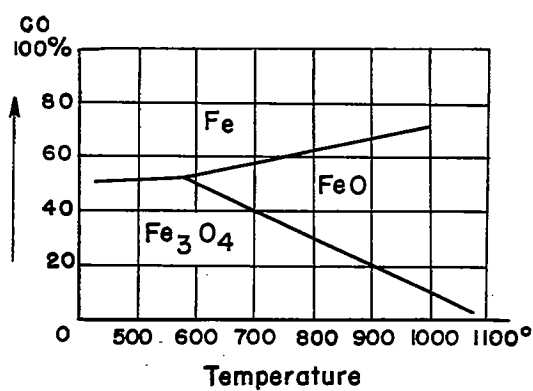


Figure 43.

Figure 44.- Equilibrium CO-CO₂-Fe and its oxides (A. Chaudron).

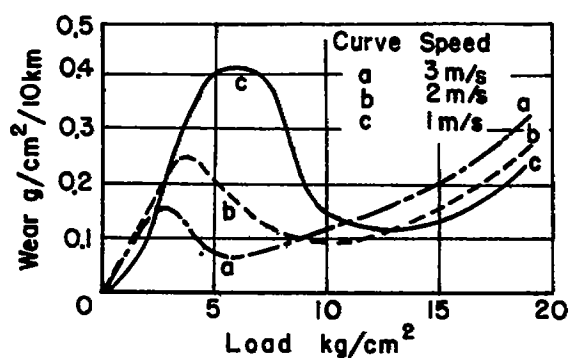


Figure 45.- Effect of sliding speed on wear.

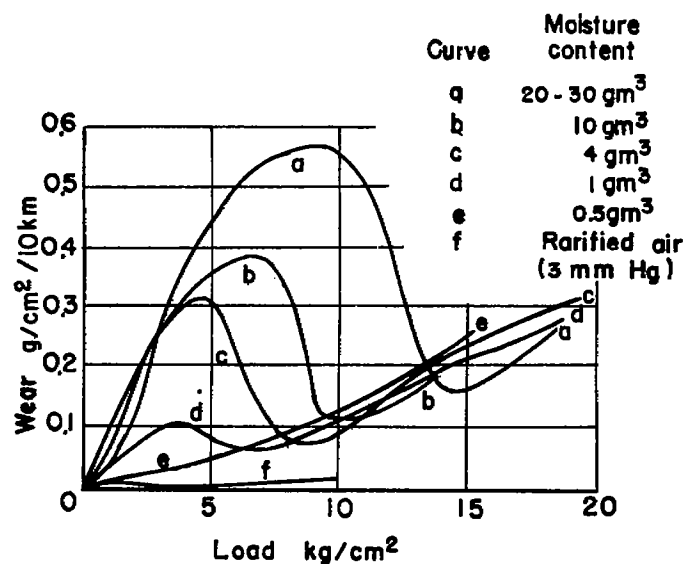


Figure 46.- Effect of moisture of air on wear of extra-soft steel.

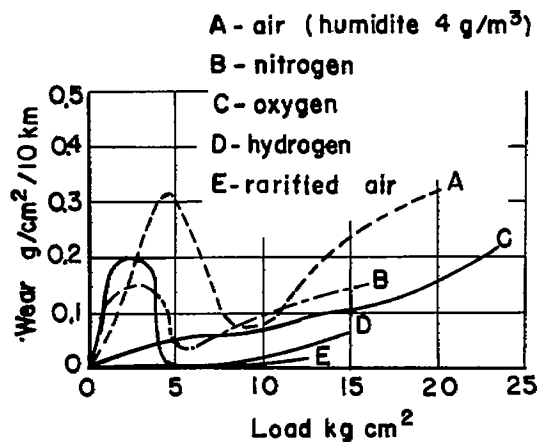


Figure 47.

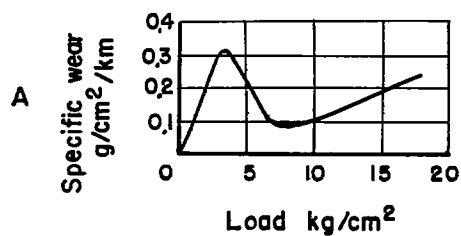


Figure 48a.- Wear of soft steel on hardened chromium steel.

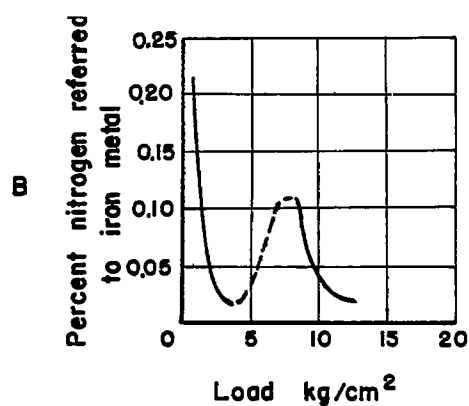


Figure 48b.- Composition of abraded dust of extra-soft steel obtained under various loads.

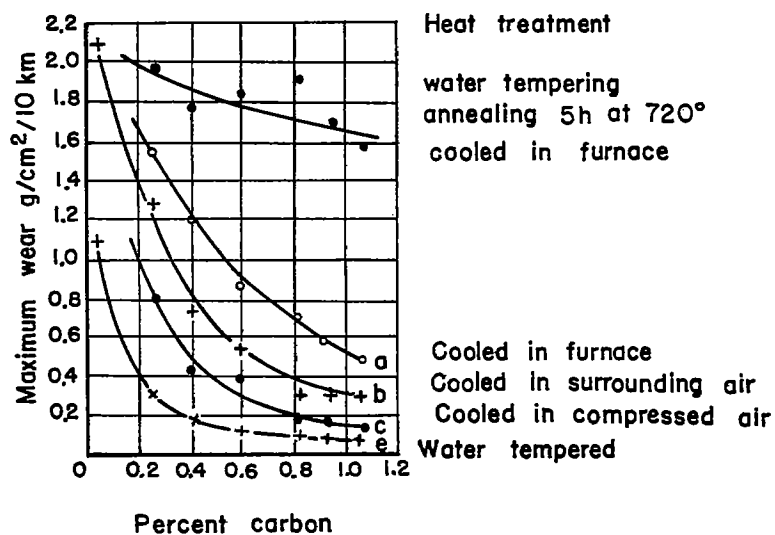


Figure 49.- Maximum wear of carbon steels A to G after different heat treatments.

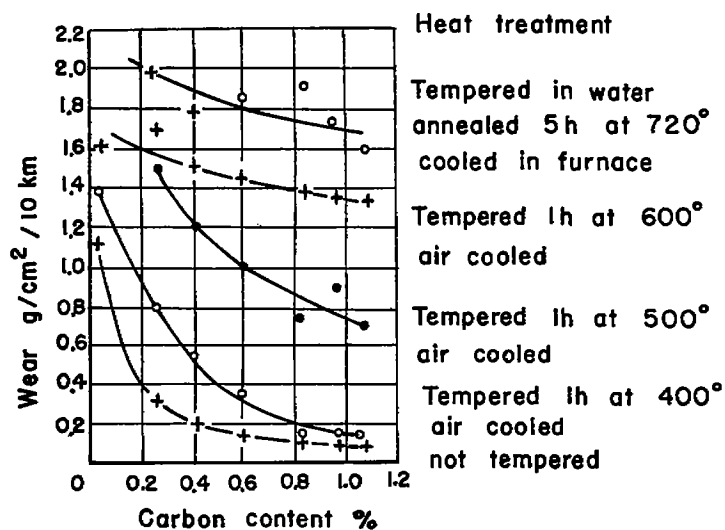


Figure 50.- Maximum wear of carbon steels A to G after different heat treatments.

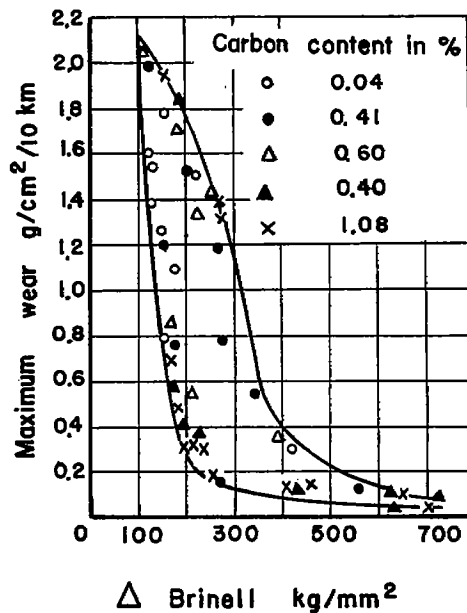


Figure 51.- Relationship between maximum wear and Brinell hardness of carbon steels at various states of heat treating.

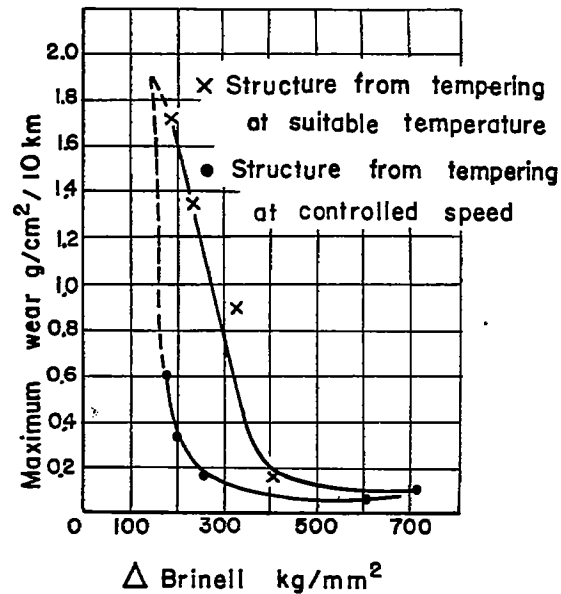


Figure 52.- Wear of steel (9.95 percent C); relationship between wear and hardness for various structures. (Ed. note: The quantity 9.95 percent C should probably be 0.995 percent C.)

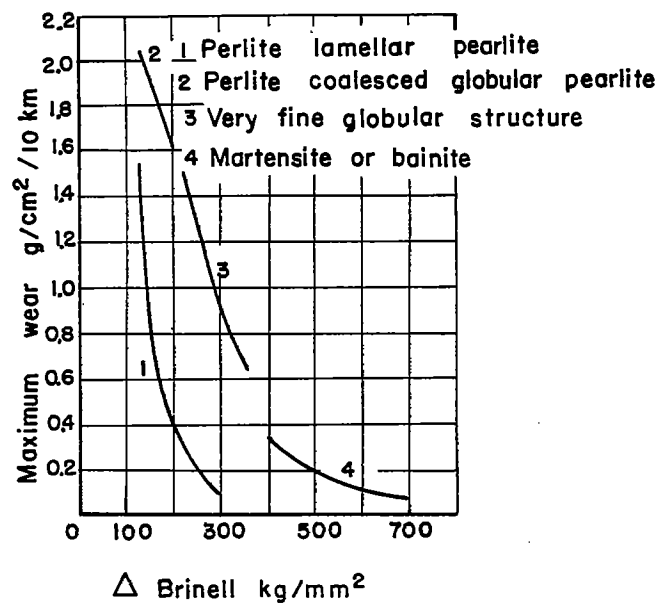


Figure 53.- Relationship between maximum wear and Brinell hardness of carbon steel of the same structure.

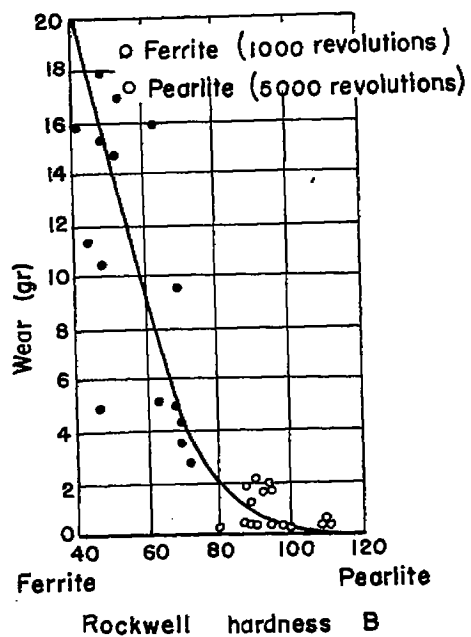


Figure 54.- Rockwell hardness (Piwowarski and Heimes).